AD-771 393

SILICON NITRIDE IN ROLLING CONTACT BEARINGS

NORTON CO.

PREPARED FOR

NAVAL AIR SYSTEMS COMMAND

OCTOBER 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

UNCLASSIFIED
Security Classification

AD771393

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Norton Company, Industrial Ceramics Division
1 New Bond Street
Worcester, Massachusetts 01606

2a. REPORT SECURITY CLASSIFICATION

2b. GROUP

3. REPORT TITLE

SILICON NITRIDE IN ROLLING CONTACT BEARINGS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final (January 3, 1973 to October 3, 1973)

5. AUTHOR(S) (First name, middle initial, last name)

H. Robert Baumgartner
David V. Sundberg
William M. Wheildon

6. REPORT DATE

October 1973

7a. TOTAL NO. OF PAGES

89

7b. NO. OF REFS

17 Tables
~~40 Figures~~

8a. CONTRACT OR GRANT NO.

N00019-73-C-0193

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Department of the Navy
Naval Air Systems Command
Washington, DC 20360

13. ABSTRACT

The Naval Air Systems Command Contract N00019-73-C-0193 investigated the applicability of silicon nitride as a bearing material. Rolling contact fatigue tests showed that hot-pressed silicon nitride (Norton NC-132) had excellent fatigue life. No fatigue failures occurred at a nominal Hertz stress of 600,000 psi for up to 93,653,000 stress cycles. Failures occurred at higher stresses by the formation of fatigue spalls. The L_{10} life of silicon nitride at a nominal 700,000 psi level was 12,000,000 stress cycles, eight times the L_{10} life of M-50 CVM steel.

Two types of precision roller bearings were designed, fabricated and tested. The first type of bearing consisted of steel races and retainer with silicon nitride rollers; the second type used silicon nitride races and rollers. Bearing designs and finishing procedures are detailed in the report. Two bearings of each type were tested under accelerated conditions to simulate the heavy outer race loading sustained in high speed operation. The bulk of the testing was performed at a speed of 10,000 rpm and 2500 pounds load. Under these conditions, the calculated L_{10} life of a similar, all steel bearing is 120 hours. The tests were highly successful and conducted without failure or serious deterioration. The tests of the two steel race bearings were suspended after 221 and 641 hours, respectively, of total test time. The two tests of the silicon nitride race bearings were suspended after 62 and 331 hours, respectively, of total test time.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ceramic						
Silicon Nitride (Si_3N_4)						
High Strength Materials						
Rolling Contact Fatigue (RCF)						
Wear						
Surface Preparation						
Ceramic Bearings						
Roller Bearings						

SILICON NITRIDE IN ROLLING CONTACT BEARINGS

FINAL REPORT
Contract N00019-73-C-0193
January 3, 1973 to October 3, 1973

H. R. Baumgartner
D. V. Sundberg
W. M. Wheildon

SUBMITTED TO:

Department of the Navy
Naval Air Systems Command
Code AIR-52032A
Washington D.C. 20360

Approved for public release; distribution unlimited

NORTON COMPANY
INDUSTRIAL CERAMICS DIVISION
WORCESTER, MASSACHUSETTS 01606

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

FOREWORD

This report covers activities carried out by Norton Company, Worcester, Massachusetts, 01606, under Naval Air Systems Command Contract N00019-73-C-0193, initiated to "investigate the utility of ceramic materials in rolling contact bearings". The work was administered under the direction of Mr. Charles F. Bersch, NAVAIR, Washington, D.C.

The following Norton Personnel were major contributors to the program in the capacity noted:

W. M. Wheildon - - - Principal Investigator 1/73 - 6/73
H. R. Baumgartner - - Principal Investigator 7/73 - 10/73
M. L. Torti - - - - - Technical Management

Mr. Wheildon officially retired from Norton Company at the end of June 1973, but has continued to contribute to the program as a technical consultant.

Bearing design and testing facilities were supplied by Federal Mogul Corporation, Ann Arbor, Michigan, 48104, under subcontract to Norton Company,

D. V. Sundberg - - - Principal Investigator

The authors wish to thank the entire Federal-Mogul Bearing Group Research Staff for their cooperation in accomplishing the objectives of the program. Special thanks are offered to R. J. Winiarski and J. C. Skurka for their engineering talent in designing and testing the full scale bearings.

ABSTRACT

The Naval Air Systems Command Contract N00019-73-C-0193 investigated the applicability of silicon nitride as a bearing material. The evaluation was based on the testing of elemental components and full-scale prototypes of silicon nitride containing bearings.

Rolling contact fatigue tests showed that hot pressed silicon nitride (Norton NC-132) had excellent fatigue life. No fatigue failures occurred at a nominal Hertz stress of 600,000 psi for up to 93,653,000 stress cycles. Failures occurred at higher stresses by the formation of fatigue spalls, the common failure mode of bearing steels. The L_{10} life of silicon nitride at a nominal 700,000 psi level was 12,000,000 stress cycles, eight times the L_{10} life of M-50 CVM steel at the same stress level. A load life exponent of 5.4 was found for the silicon nitride.

Two types of precision roller bearings were designed, fabricated and tested. The bearings were full-scale with 55 mm bores. The first type of bearing consisted of steel races and retainer with silicon nitride rollers; the second type used silicon nitride races and rollers. Bearing designs and finishing procedures are detailed in the report. The design operating conditions were for speeds up to 65,000 rpm and radial loads up to 400 pounds.

Two bearings of each type were tested under accelerated conditions to simulate the heavy outer race loading sustained in high speed operation. The bulk of the testing was performed at a speed of 10,000 rpm and 2500 pounds load. Under these conditions, the calculated L_{10} life of a similar, all steel bearing is 120 hours. The tests were highly successful and conducted without failure or serious deterioration. The tests of the two steel race bearings were suspended after 221 and 641 hours, respectively, of total test time. The two tests of the silicon nitride race bearings were suspended after 62 and 331 hours, respectively, of total test time.

SUMMARY

This investigation was concerned with the evaluation of hot pressed silicon nitride as a bearing material. Its organization may be divided into three principal activities: 1) rolling contact fatigue testing of silicon nitride rod specimens 2) the design and fabrication of two types of high speed, silicon nitride containing, roller bearings and 3) the accelerated testing of these full-scale roller bearings.

The Rolling Contact Fatigue (RCF) test machine is a rapid method of evaluating bearing materials under load. A small rod specimen is loaded between two relatively large diameter opposing crowned wheels that apply pressure while the specimen is driven at 10,000 rpm. The specimen receives two stress cycles per revolution, resulting in 1.2×10^6 test cycles per hour. All testing was carried out with conventional lubrication.

All the silicon nitride material used in the study was Norton NC-132 silicon nitride. This material is a newer, more uniform grade of silicon nitride which has a lower frequency of large inclusions.

RCF testing was conducted with steel loading wheels at nominal (calculated for the unlubricated condition) Hertz stress levels of 600 M, 700 M, 750 M and 800 M psi. Silicon nitride exhibited excellent fatigue life, the attainment of which fully verified the hypothesis, promulgated in the previous contract period, that surface preparation technique can control fatigue life. No failures occurred at the 600 M psi stress level even after testing up to 93,000,000 cycles. The L_{10} life, the number of cycles at which ten percent of the bearing elements will fail, of silicon nitride was eight times that of M-50 CVM steel at the 700,000 psi stress level. A condensed table of the most significant RCF results are given below:

Condensed RCF Results

Material	Nominal Hertz Stress	Number of Tests	L_{10} Life (stress cycles)
Si_3N_4	600	16	no failures
Si_3N_4	700	16	12,000,000
Si_3N_4	800	11	1,500,000
M-50 CVM	600	--	2,380,000
M-50 CVM	700	12	1,600,000

Based upon the load-life data at 700 M and 800 M psi and

assuming that a load-life equation of the form applicable to steel:

$$L_{10} = \left(\frac{\text{bearing capacity}}{\text{load}}\right)^n$$

where, n = load-life exponent

,also applies to silicon nitride, a load life exponent of 5.4 is found.

The RCF rods were examined by dye penetrants, scanning electron microscopy and an electron probe. Penetrant tests revealed that each failed test track and some of the suspended test tracks were bordered by Hertz cracks. No cracking was observed for the tests run at 600 M psi and the incidence of cracking increased with loading. A very large majority of the fatigue failure spalls originated from antecedent Hertz cracks. No instances of inclusion initiated spalling was observed in the uniform silicon nitride. These observations lead to speculation that silicon nitride may possess a fatigue limit which is above the stresses normally encountered in actual bearings.

Limited RCF testing was done using silicon nitride load wheels at 600 M, 700 M and 800 M psi levels. Single tests at 600 M psi and 700 M psi resulted in test suspensions at 105 and 147 million stress cycles, respectively, and two failures were obtained at the 800 M psi level. This testing was terminated due to early load wheel failures caused by the inability of the wheels to withstand Hertz crack formation. This condition was detected by dye penetrants and resulted from inadequate, for the high stresses involved, surface finishing of the load wheels.

Two types of precision, aircraft-type, roller bearings, containing silicon nitride components, were designed, fabricated and tested. The bearings had a 55mm bore and twenty rollers. The first bearing type utilized M-50 steel races, NC-132 silicon nitride rollers, and an AISI 4340 silver plated roller retaining ring. The design for this bearing had been completed in the previous contract period, as had the fabrication of the steel races and all retainers. Design operating conditions for the bearings were speeds up to 65,000 rpm and radial loads up to 400 pounds.

Prior to roller manufacture, the NC-132 silicon nitride billet stock reserved for the rollers was qualified by RCF testing, as were the finishing procedures to be used on the roller blanks. The rollers were fabricated in two steps. Firstly, diamond grinding and lapping techniques were used to produce slightly oversized diameter roller blanks. Secondly, a "K" crown was plunge ground onto the rollers with a silicon carbide wheel. Less than 0.001 inch of stock was removed in this final roller finishing operation.

The second type of bearing utilized silicon nitride inner and outer races in addition to the silicon nitride rollers. The bearing was designed during the current contract program and was a modification of the steel race bearing to permit the use of the same type of roller. A special fixturing method was used to attach the ceramic inner race to the bearing shaft in order to accomodate the difference in thermal expansion between the steel shaft and the ceramic bearing. The silicon nitride races were formed by diamond grinding and lapping procedures.

The finished components were carefully dimensioned and met print tolerances with few minor exceptions. The rollers were divided into matched groups of twenty each. Three bearings of each type were assembled.

Two bearings of each type were tested under accelerated test conditions which were intended to simulate the high outer race loading experienced during high speed bearing operation. The test conditions are outlined below:

Radial Load:	500 to 2500 pounds
Speed:	1200 to 10,000 rpm
Temperature:	170° to 190°F
Lubricant:	Enco 2380 Type II Turbo Oil Oil recirculated through 10 micron filter.

The majority of the testing was under the accelerated load of 2500 pounds and 10,000 rpm. The AFBMA calculated life at the L_{10} rank for a similar bearing made of steel and run under these conditions is 120 hours.

The full scale bearing tests were highly successful, without bearing failure or deterioration. The two steel race-silicon nitride roller bearing tests were suspended after 76 and 640 hours, respectively, at 2500 pounds of load and 10,000 rpm. The 640 hour tested bearing showed slight outer race scuffing caused by roller edge loading due to deflection of the bearing assembly in the test stand. Although loading at the scuffed region exceeded the expected 310,000 psi calculated nominal loading, the bearing did not fail. Wear was minimal and was composed mainly of steel outer race wear. The diametral clearance of the bearing did not change during test. Both bearings could have been tested further.

The two silicon nitride race and roller bearings were successfully suspended after 62 and 331 hours of total running time. The longer tested bearing was under 2500 pounds load for 310 hours. The outer race load zone on this bearing showed a maximum wear depth of 25 millionths of an inch. The bearing was in excellent condition and could have been tested further.

I. INTRODUCTION

Ceramic materials offer many interesting properties which suggest their use in bearings. Among these are; light weight, high mechanical strength in compression, resistance to corrosion, low coefficient of friction, dimensional stability, and high hardness over a wide temperature range. In addition they are generally further characterized by high resistance to wear, low coefficient of thermal expansion, very high melting point, and the ability to hold close tolerances and fine finishes. Because of the desirability of many of these properties, extensive studies have been conducted with both solid ceramic and ceramic coatings for sliding and plain bearings. This work has lead to wide use of ceramic containing plain bearings in industry.

Though numerous studies have been conducted and others are continuing with ceramics for plain and gas bearings, limited work has been devoted to ceramics for rolling contact (ball and/or roller) bearings. More importantly, even less work has been done with what might be termed advanced ceramics. Advanced ceramics would include those materials having very high cross-bending strengths, very fine grain size, high density, and a very homogeneous structure. These properties plus stable characteristics at elevated temperatures has identified advanced ceramics as excellent potential candidate materials for applications involving rolling contact environments at elevated temperatures such as aircraft engine roller bearings. For background, Appendix I summarizes much of the work to date with ceramics in rolling contact.

High rotational speeds developed in modern jet engines have changed the common failure mode of both roller and ball bearings to the outer race instead of the inner race. The high centrifugal forces of the rollers developed by the increased speeds have loaded the outer races to the point where they must endure higher stresses than the inner races. Hollow steel balls have been investigated but fabrication problems influencing balance limits their usefulness at high speeds. Light weight ceramics with specific gravities two-fifths that of steel would greatly reduce centrifugal loading even when used in the solid form.

The present program was undertaken to investigate high strength ceramics as rolling contact bearing for aircraft engine applications. The program is broadly divided into two phases: (1) materials investigation and evaluation and (2) full bearing fabrication and testing.

II. FATIGUE TESTING OF ELEMENTS

A. Introduction

The Rolling Contact Fatigue (RCF) test machine was the primary means of evaluating material fatigue life throughout the program. Previous RCF testing on hot-pressed silicon nitride[1] gave encouraging fatigue lives; the silicon nitride life being in excess of that for M-50 CVM bearing steel. The RCF test method was capable of differentiating between different methods of silicon nitride surface preparation and variations in material density. The fatigue life of silicon nitride was found to be sensitive to surface preparation. Improper finishing procedures left subsurface damage which resulted in fatigue life an order of magnitude less than that of properly finished specimens. Proper surface preparation was achieved by the use of progressively finer diamond abrasives. It was also shown that the removal of a small amount of material from a properly prepared surface by silicon carbide grinding did not have a detrimental effect on fatigue life.

The RCF test method was used in the current program to a) qualify the silicon nitride material used in other program phases, b) evaluate and qualify the finishing procedures to be used to produce roller blanks destined for use in bearings, c) establish the load versus fatigue life relationship of NC-132 silicon nitride in rolling contact with steel and d) to investigate the behavior of silicon nitride rolling on itself.

B. Description of RCF Equipment

The Rolling Contact Fatigue test machine developed by General Electric Company and marketed by Polymet Corporation is shown in Figure 1. Two discs, seven inches in diameter and one-half inch thick, are pressed against the rotating test specimen. The discs have a crown radius of 0.250 inches. The test specimen is a three inch long straight cylinder with a diameter of 0.375 inches. With this geometrical configuration, the contact stresses can be calculated (in the non-lubricated condition) for a given load, as is shown in Appendix II. For example, for a load of 325 pounds, the maximum Hertz stress developed between a steel test specimen and steel loading wheels is 700,000 psi. The load necessary to produce this stress in a silicon nitride specimen with a steel wheel is approximately 15 percent less because of the higher modulus of elasticity of the ceramic .

The RCF machine provides a means of rapid testing in nearly pure rolling contact. Since the specimen receives two stress cycles per revolution, the specimen receives 1,200,000 stress cycles per hour when driven at 10,000 rpm. The fatigue life of a test is defined either by the number of cycles incurred before

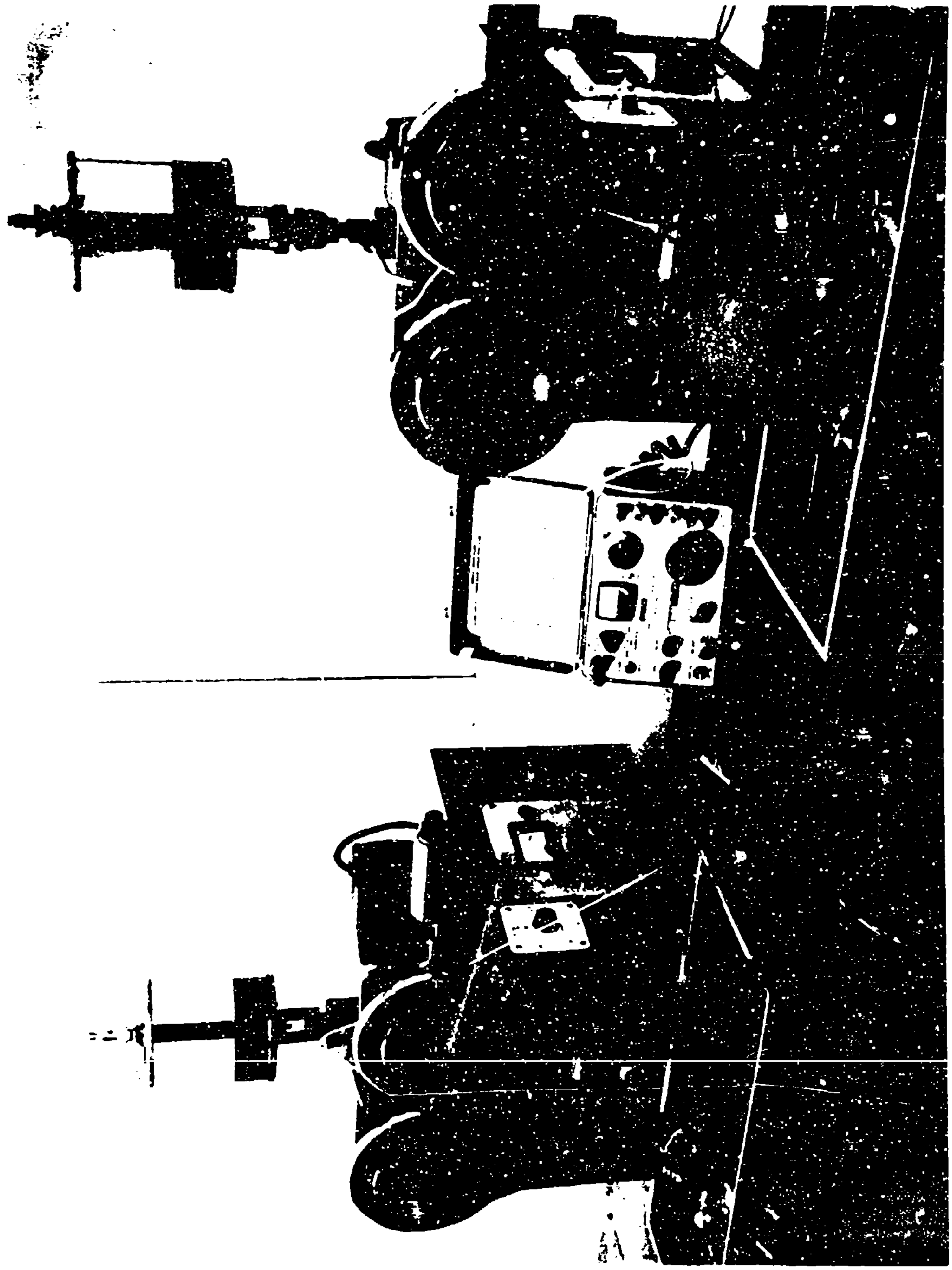


FIGURE 1 - Rolling Contact Fatigue Test Machines

spall formation, which produces jig vibrations that are picked up by a sensor which automatically triggers test termination, or by the number of cycles sustained before test suspension at an arbitrarily high number of cycles. The average M-50 tests is about 3,500,000 cycles, so an average test lasts three hours. In contrast the average "accelerated" full scale bearing test has a duration of about 500 hours.

The loading discs see a stress comparable to that of the test specimen, but their relatively larger diameter normally provides them a longer life than the specimens. However, they require refinishing when they spall or flatten, usually after 20-30 tests on steel specimens for steel discs. The wheels are requalified after grinding by testing on a controlled group of M-50 steel specimens.

The test conditions of the RCF machines used throughout this program are given in Table I.

TABLE I

RCF Test Conditions

Load:	89 to 325 pounds
Temperature:	70°F to 80°F
Speed:	10,000 rpm
Lubricant:	Humble Enco 2380 Type II Turbo Oil (MIL-L-23699B)
Specimen Geometry:	0.375" ± 0.0002" diameter x 3" Surface finish less than 6 μin.AA Roundness within 0.0001"

C. Description of Silicon Nitride Material

All of the silicon nitride used in the current program was Norton NC-132 silicon nitride. This material is an evolutionary refinement of the Norton HS-110 and HS-130 silicon nitrides used and described in previous research[1]. Like them, it is a dense hot pressed silicon nitride, however, it possesses a more homogeneous microstructure as a result of the size and number of inclusions having been reduced. This greater structural uniformity gives greater strength and is desireable in a bearing material as inclusions were found to initiate spalling failures in the earlier silicon nitrides. The average flexural strength of Norton NC-132 silicon nitride, measured in four point bending, is in excess of 125,000 psi. The chemical composition of this material

is similar to that of HS-130 silicon nitride and a typical emission spectograph analysis of its major metallic constituents is given in Table II.

TABLE II

Typical Chemical Analysis
of Norton NC-132 Silicon Nitride

Metallic Element	Weight Percent
Al	0.7
Fe	0.4
Ca	0.03
Mg	0.7
W	∿ 1.5 - 2

D. Specimen Preparation

A total of twenty-five silicon nitride rods for rolling control fatigue testing were prepared. The rods were labeled 73-1 through 73-25. Two rods, one from each of two billets, were used to qualify the billet stock allocated for the production of the rollers for the full bearings. Two other rods were cut from the same billets and used to evaluate the finishing techniques to be used in the preparation of the roller blanks prior to final crowning. These four rods were removed from the central portions of the 6" x 6" x 1" billets. Final rod densities ranged between 3.28 and 3.31 g/cc, within the normal density range for NC-132 silicon nitride. The remaining twenty-one other rods were excised from a third billet and reserved for load-life testing.

The finishing procedures on the RCF rods used for billet qualification and load-life studies were identical and as follows: Bars, 6" x 7/16" x 7/16", were sliced from the billets and mounted between centers on an O.D. cylindrical grinder. The bars were rough ground from a square to a round cross-section with a 100 diamond grit, resinoid bonded wheel. The rods were finish ground with a 320 diamond grit, resinoid bonded wheel. A minimum of 0.005 inch of stock was removed with the 320 grit wheel. The machine conditions employed are listed in Table III.

The final finish was imparted by decreasing the infeed to 0.0005" per pass for the last few passes and then allowing the wheel to run out. The rods were then sliced to the useable three inch length.

TABLE III

RCF Rod Machining Conditions

Wheel Speeds:	5500 sfpm
Work Speeds:	600 rpm
Traverse Feed:	0.001"/work revolution
Wheels:	ASD100-R75B69 (roughing) ASD320-N75B69 (finishing)
Infeeds:	0.0015"/pass (roughing) 0.001"/pass (finishing)
Coolant:	Norton Wheelmate 203

The twenty one rods allocated for the load-life testing were examined for roundness, surface finish and density. The results of these measurements are shown in Table IV. The best fourteen of these rods were chosen for actual testing. A typical ground surface of an RCF rod is shown in Figure 2.

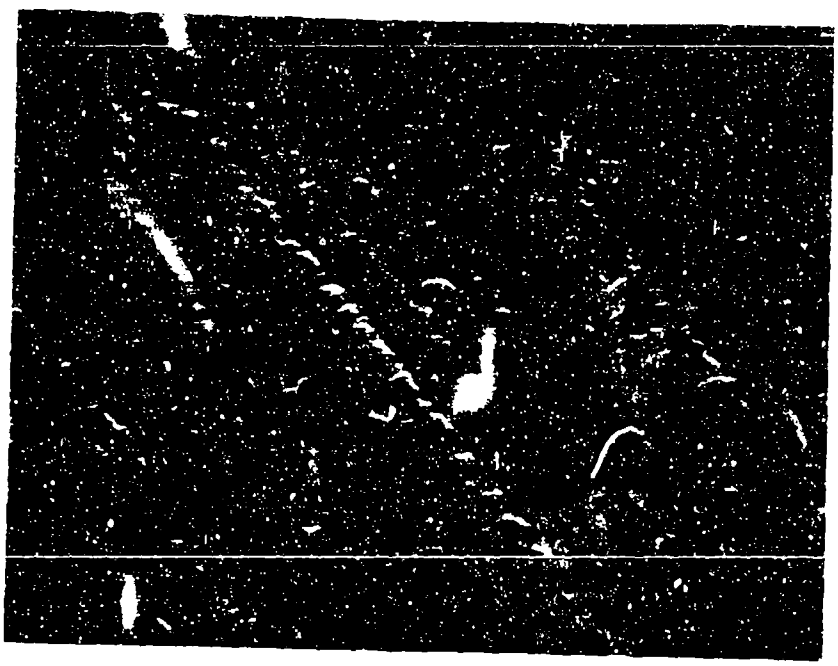


FIGURE 2 - Ground (320 diamond grit) Surface of Silicon Nitride Rod, SEM, 2000X.

TABLE IV

RCF Bar Dimensions, Surface Finish and Density

Bar #	Out-of-Roundness Millionths of an Inch (Total)	Surface Finish micro inch AA	Density g/cc
73-3	85	5 - 5.5	n.m.
-4*	50	4 - 4.5	3.28 ±0.01
-5*	50	4.5 - 5	3.28
-6	85	5 - 5.5	n.m.
-7*	35	3.5 - 4	3.29
-8	125	5 - 5.5	n.m.
-9*	30	4.5 - 5	3.29
-10*	80	4.5 - 5	3.29
-11*	65	4.5 - 5	3.28
-12*	40	4 - 4.5	3.29
-13*	50	5 - 5.75	3.32
-14	65	5 - 5.5	n.m.
-15	275	5 - 5.3	n.m.
-16	75	4.5 - 6	n.m.
-17*	65	4 - 4.5	3.29
-18*	60	4.8 - 5	3.32
-19	65	5.5 - 6	n.m.
-20	85	4.5 - 5	3.30
-21*	45	4 - 4.5	3.29
-22*	85	4.5 - 5	3.32
-23*	100	4 - 4.5	3.31

*Indicates RCF bars tested. n.m. = not measured

Material sufficient to produce two RCF rods was sent to the vendor selected to finish the full bearing roller blanks. These rods were finished with the procedure anticipated for finishing the roller blanks. The purpose for the rods was to ensure, by prior RCF testing, that the roller finishing technique would be satisfactory.

The 7/16" square bar stock was ground to a round cross-section by the use of a 120 diamond grit, resinoid bonded wheel on a surface grinder with a cylindrical grinding attachment. The rods were reduced in diameter on a centerless grinder which used a 220 diamond grit, resinoid bonded wheel. A total of approximately 0.030" was removed in steps and the wheel allowed to run out in the final passes. All grinding was done wet. Final finishing was achieved by the use of six micron diamond paste in a cast iron ring lap which was hand held against the rod as it was rotated at 200 rpm. A maximum of 0.0001" of material was removed from the rod radius by this lapping operation. Final surface roughness was 2 microinches (AA).

Loading discs of HS-130 silicon nitride were fabricated for the silicon nitride rolling on silicon nitride contact studies. The 7-1/8" O.D. X 4-1/8" I.D. X 1/2" thick disc blanks were fitted with a ball bearing and axial shaft assembly mounted in the I.D. The shaft was adaptable to the RCF test machine and was used to assure disc concentricity during generation of the 1/4 inch radius of the circumferential crown. The square edges of the disc blanks were removed by O.D. grinding two 45 degree chamfers on a disc with a 100 diamond grit, metal bonded wheel. The shaft of the disc was then mounted in a jig grinder to generate the crown. The rotational speed of the disc was kept small during the roughing-in of the 1/4 inch radius. As the shape was more perfectly formed, the disc was allowed to rotate on its shaft at 20-40 rpm. A minimum of 0.020 inch of stock was removed with the jig grinder. All grinding was done wet. A hand held pine stick and three micron diamond paste were used to impart the final finish. This lapping operation removed less than 0.0001 inch.

The diameters of a set of two loading wheels were matched to within 0.0002 inch, the nominal diameter being seven inches. A finished set of silicon nitride loading wheels are shown in Figure 3. Plastic shields were used to protect the ball bearings from wear debris.

E. Test Results

1. Qualification of Roller Billet Stock and Evaluation of Roller Blank Finishing Technique.

The silicon nitride billet stock to be used for roller blanks was qualified by testing two RCF rods of this material.

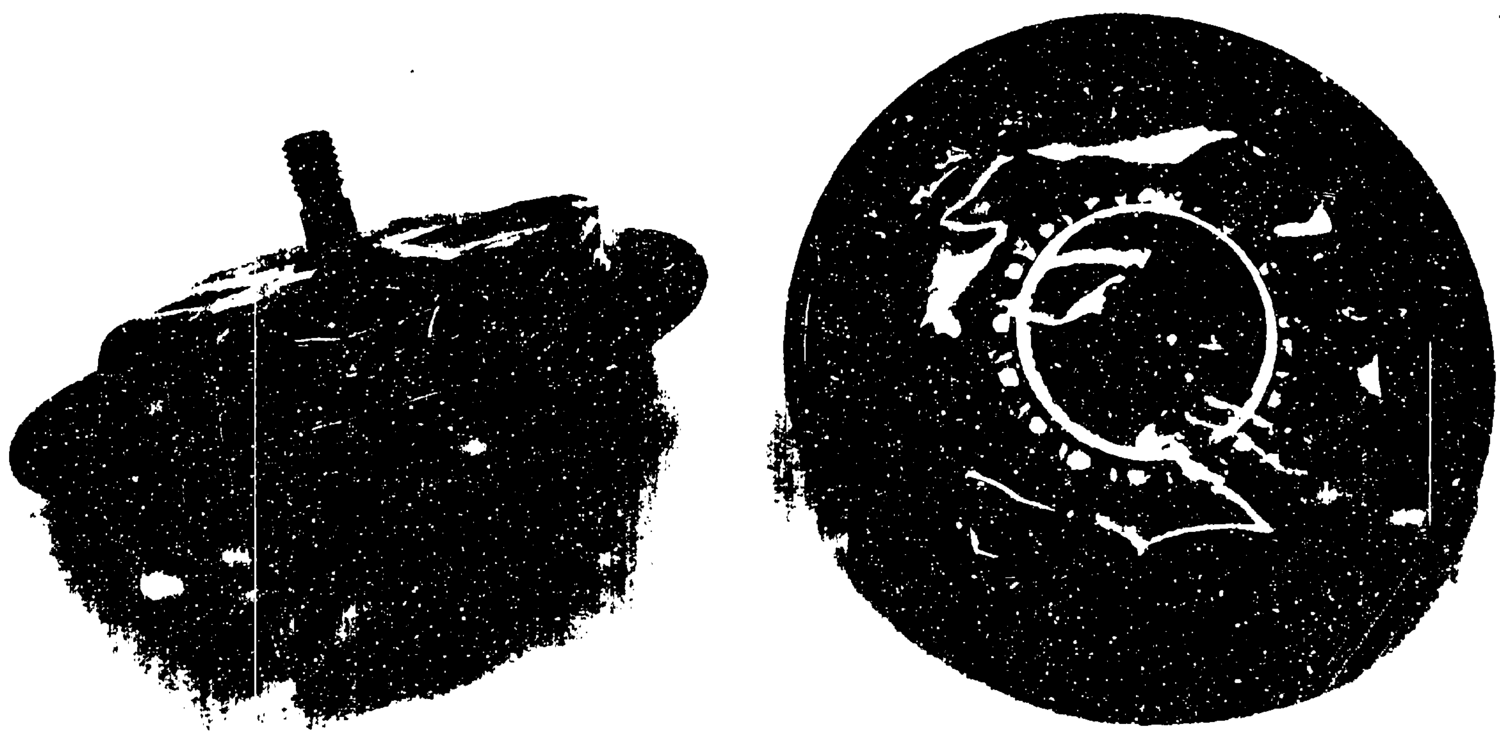


FIGURE 3 - Silicon Nitride Loading Wheels for the RCF Tester

Twelve tests were performed at a 800 M psi Hertz stress and are reported in Table V. The fatigue lives ranged from 2,600,000 to 19,600,000 stress cycles, within the acceptable range for this stress level.

TABLE V

RCF Test Results for Roller Billet Qualification and Surface Finish Evaluation

Billet Qualification

Test Bar #	Fatigue Life x 10^{-6} Cycles (800 M psi Hertz)
73-1	2.6, 2.7, 3.2, 3.6, 4.4, 6.3
73-2	6.5, 10.5, 10.5, 12.7, 14.1, 19.6

Surface Finish Evaluation

As Received Test Bar #	Fatigue Life x 10^{-6} Cycles (800 M psi Hertz)
73-24	0.7, 0.7, 1.0, 1.3, 1.6, 6.0, 6.4, 6.5
73-25	1.2, 1.3, 2.0, 2.7, 3.1, 3.4
After Resurfacing:	
73-25	2.1, 3.7

The two rods prepared with the technique intended as the finishing method for the roller blanks were tested at a 800 M psi Hertz stress. The fourteen test results are recorded in Table V. These lives were only fair, with some lives below a million cycles. These results caused a revision in the finishing procedures (to be detailed later) used on the roller blanks.

These rods were refinished by procedures more closely related to the revised roller blank finishing procedures and then retested. An additional 0.0004 inch was removed from the diameter of these rods by the sequential use of six and three micron diamond paste in the ring lap. A micrograph of this finish is shown in Figure 4. Two additional RCF tests were run. The results appear in Table V and fall within the range previously established for the rod. Since these rods were cut from the same billets as the longer lived 73-1 and 73-2 rods, their slightly inferior performance is attributed to a greater residual sub-surface damage condition as a result of being ground with the 220 grit wheel as opposed to the 320 grit wheel used on rods 73-1 and 73-2.

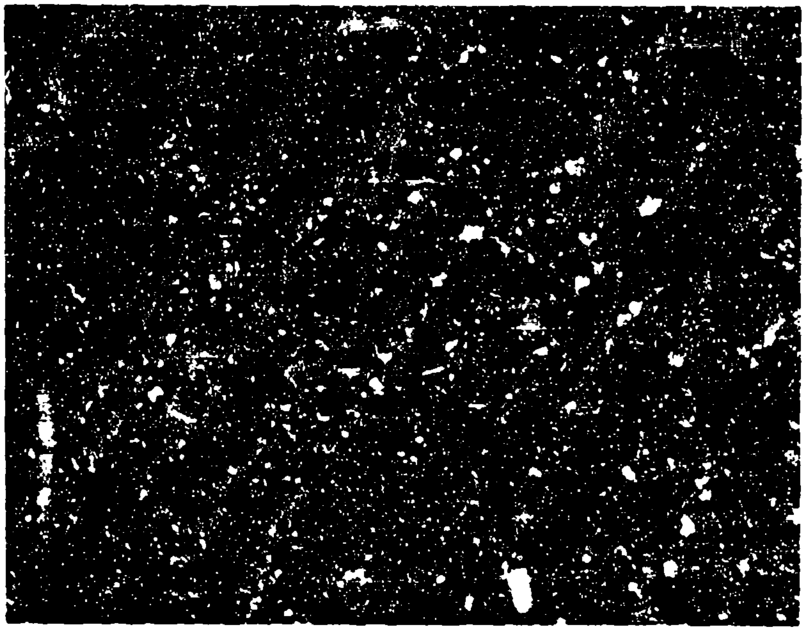


FIGURE 4 - Sequentially Lapped Silicon Nitride Surface, SEM, 2000X.

2. Steel Loading Wheels on Silicon Nitride

The load-life testing with steel loading wheels was conducted at four different loads which resulted in calculated (unlubricated condition) maximum Hertz stresses of 600 M, 700 M, 750 M and 800 M psi. The loads required to induce these stress levels are given in Appendix II. The stress cycles to failure or suspension for each test are shown in Table VI. All failures resulted from the formation of fatigue spalls.

The fatigue lives for silicon nitride and M-50 CVM steel, the latter obtained during requalifications of the loading wheels, are summarized in Table VII. No failures were observed at the 600 M psi level, even for tests up to 93 million cycle duration. The data were treated by Weibull probability statistics[2]. Figure 5 shows the Weibull functions of the silicon nitride data for the three stress levels having fatigue failures. The reason for the seemingly out of place 750 M psi plot could be the small number of failures obtained at this stress level. Figure 6 shows the Weibull plots for silicon nitride and M-50 CVM steel at 700 M psi, the Hertz stress normally used to evaluate bearing steels on the RCF. The silicon nitride has approximately eight times the fatigue life of M-50 CVM steel at the L_{10} rank.

TABLE VI

RCF Test Results of Steel-Silicon Nitride
Life in Stress Cycles X 10^{-3}

Bar #	600 M psi Hertz	700 M psi Hertz	750 M psi Hertz	800 M psi Hertz
73-4	62,001 S	15,249 F		4,394 F
73-5	43,131 S	141,538 F	125,737 S	
73-7	49,305 S	107,006 S	67,065 F	
73-9	51,441 S	32,574 F	19,715 F	
73-10	63,481 S	82,096 F		9,465 F
73-11	58,648 S	35,628 S 17,544 F	97,637 S	
73-12	84,347 S	67,670 S	100,611 F	4,239 F
73-13	82,239 S 62,589 S 82,425 S	83,512 S 113,439 S	51,587 F	1,347 F
73-17	62,012 S	3,847 F		2,842 F
73-18	64,135 S	98,517 S		30,947 F
73-20	40,165 S	24,007 F		6,310 F 4,588 F
73-21	60,297 S	48,503 F		47,362 F
73-22	30,916 S	69,813 S		29,130 F
73-23	93,653 S	72,473 S		28,272 F

S - Suspension
F - Failure

TABLE VII

Summary of RCF tests on Silicon Nitride and M-50 CVM Steel as a Function of Loading

Hertz Stress (psi)	Silicon Nitride	M-50 CVM
600 M	16 suspensions in range of 30.92 - 93.65 million cycles	L_{10} = 2.38 million cycles L_{50} = 3.70 million cycles
700 M	6 failures in range of 3.85 - 141.54 million cycles 10 suspensions in range of 32.57 - 113.44 million cycles	L_{10} = 1.60 million cycles L_{50} = 2.58 million cycles
750 M	4 failures in range of 19.72 - 100.61 million cycles 2 suspensions at 97.64 and 125.74 million cycles	No tests conducted
800 M	11 failures in range of 1.35 - 47.36 million cycles	Testing caused excessive deformation of the steel bars.

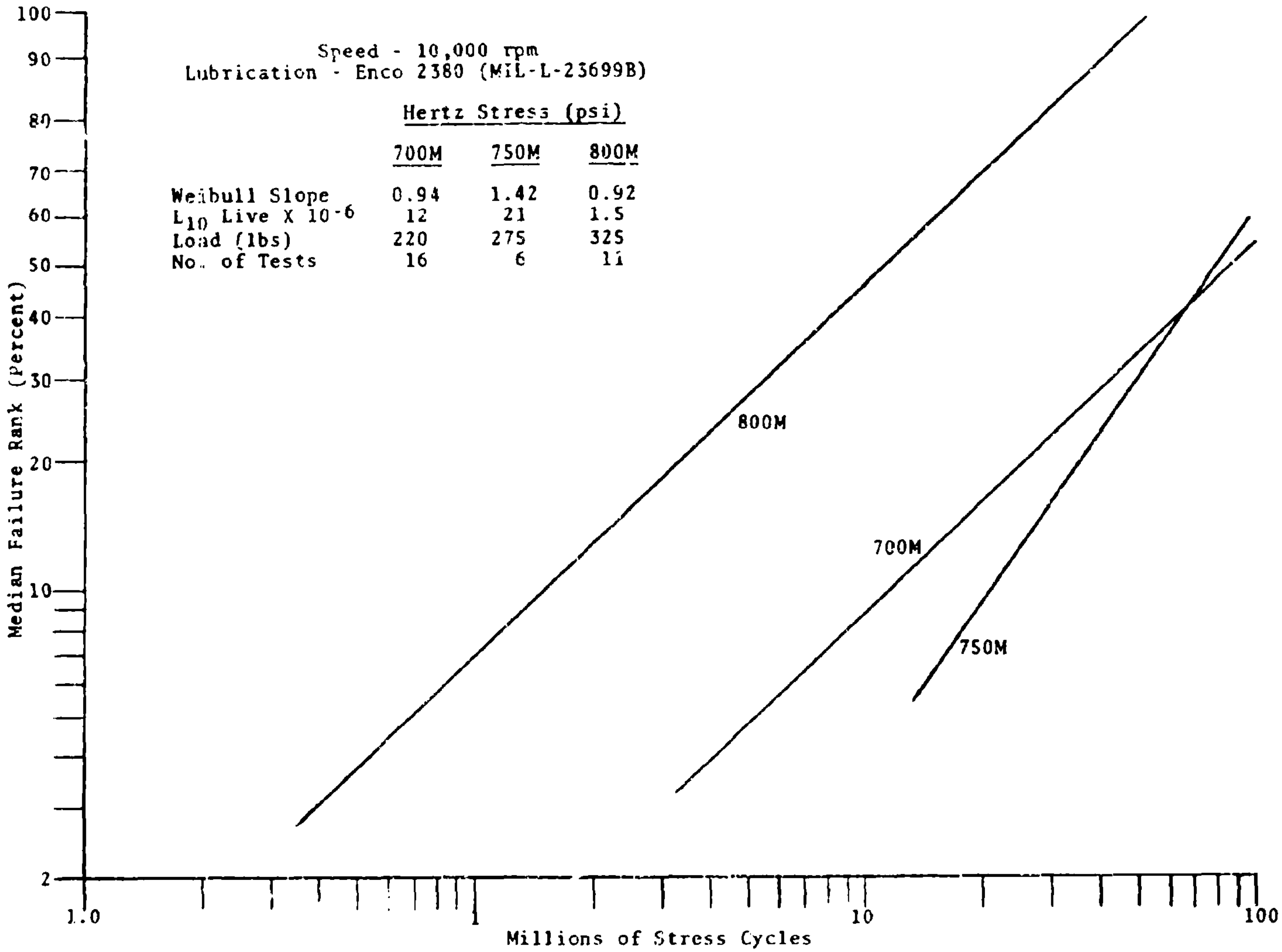


FIGURE 5 - RCF Test Results on Silicon Nitride vs. Load

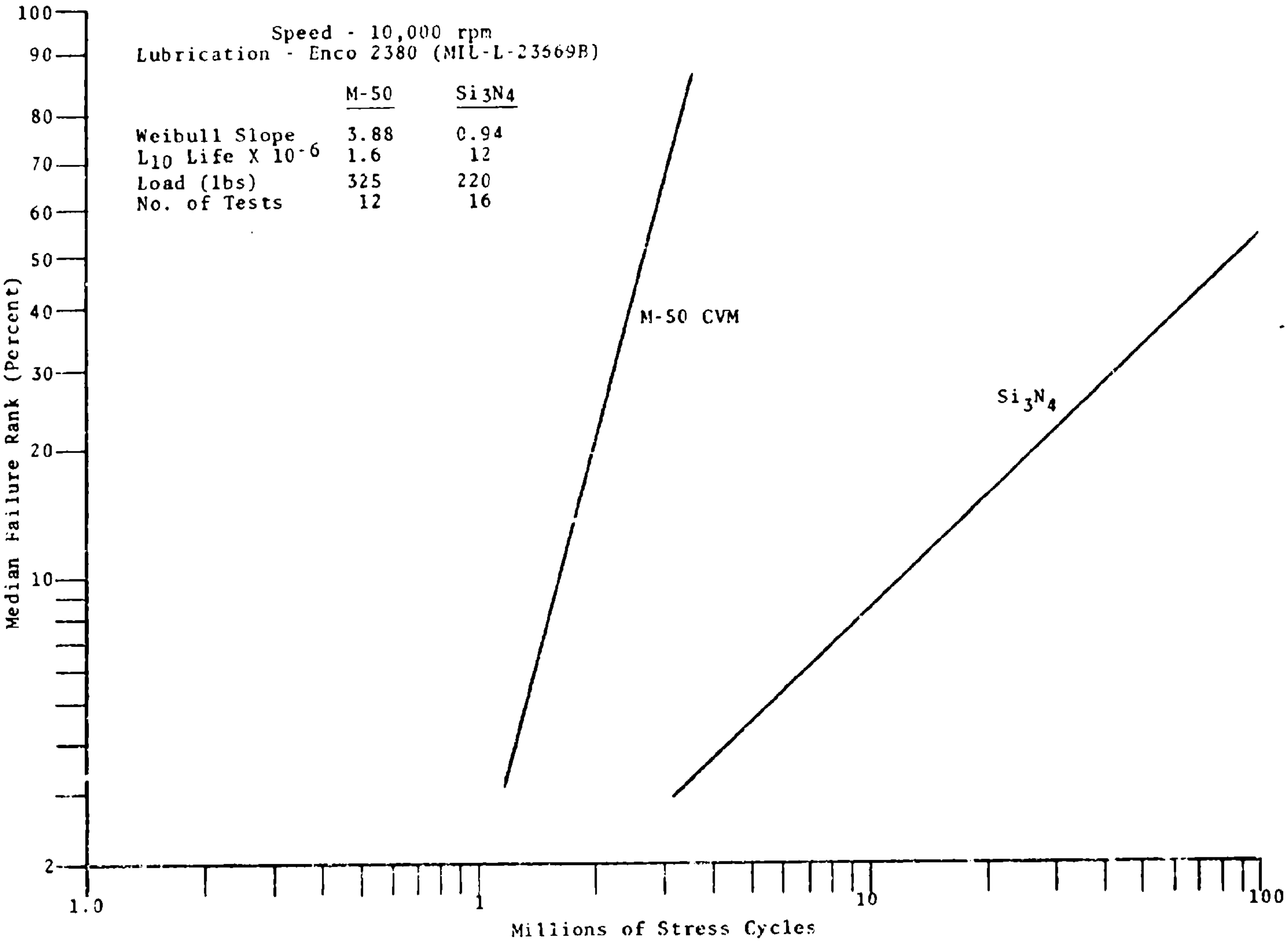


FIGURE 6 - RCF Test Results on Silicon Nitride and M-50 CVM at 700 M psi Hertz Stress

Using the L_{10} lives for the 700 M and 800 M psi stress levels and the loads to give these stresses, the RCF load-life relationship for steel on silicon nitride may be calculated from the equation:[3]

$$L = (C/P)^n$$

where $L = L_{10} \times 10^{-6}$

C = Capacity, the load at which 90% of the bearings will survive a given number of stress cycles.

P = Load

n = Load-life exponent

Using the following loads and corresponding lives from Figure 5:

$$P_1 = 325 \text{ lbs} \; ; \; L_1 = 1.5$$

$$P_2 = 220 \text{ lbs} \; ; \; L_2 = 12.0$$

, The exponent is found to be n = 5.4. This value is considered reasonable for accelerated testing. The steel-steel RCF load-life exponent calculated from the M-50 CVM data is 3.5, which is near the 10/3 or 3 value used in AFBMA calculations for roller and ball bearing capacities, respectively.

3. Silicon Nitride RCF Rods and Load Wheels

Calculations were made of the loads required to produce Hertzian stresses of 600 M, 700 M and 800 M psi for the silicon nitride load wheels in contact with the silicon nitride RCF rods. These values are listed in Appendix II.

It was originally planned to qualify the surface finish of the silicon nitride wheels by running them on M-50 CVM steel samples to verify that fatigue lives similar to those obtainable with steel loading wheels would be achieved. Testing was initiated at the 700 M psi Hertz stress level, however, the silicon nitride load wheel spalled after 23,718,000 stress cycles during the second test. Figure 7 shows this spalling.

The load wheels were reground to remove the spalls, but because of the short time remaining for this phase of the program, testing was begun on the silicon nitride rods without a qualification test for the wheels. Table VIII shows the fatigue lives obtained. One load wheel spalled during the fourth test. Although a second set of silicon nitride load wheels were prepared, they were not received in time to permit further testing. A load-life relationship for the silicon nitride/silicon nitride rolling couple could not be determined due to the lack of data.

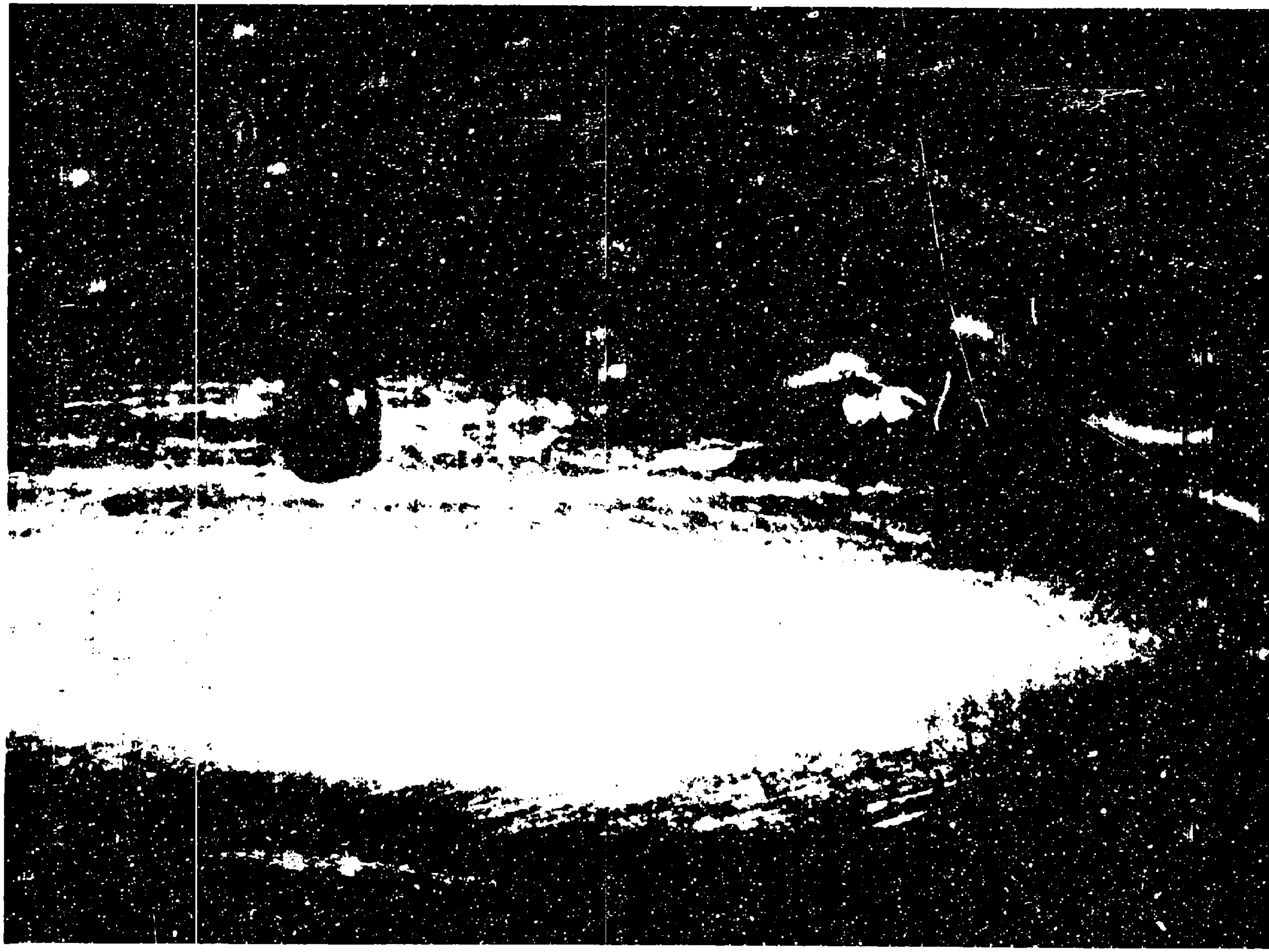


FIGURE 7 - Close-Up of Spalled Silicon Nitride RCF Test Load Wheel

TABLE VIII

Silicon Nitride on Silicon Nitride RCF Results

Bar #	Life in Stress Cycles x 10^{-3} 600 M psi	700 M psi	800 M psi
73-9			45,780 F
73-10	105,166 S	146,812 S	24,986 F*

S = Suspension
F = Spall Failure
*Load wheels failed also

During the early stages of RCF testing with newly finished silicon nitride load-wheels, black wear debris was found. The rate of debris formation decreased with running time, suggesting that the debris originated from the load wheels. A small wear sample was recovered from the splash shield of the RCF machine for later identification and particle size analysis.

F. Post-Test Examination of Components

1. Examination of RCF Rods

During the course of the previous year's contract, scanning electron microscopy revealed that many of the RCF rods possessed circumferential cracks which bordered the contact zone. An example of this cracking is shown in the scanning electron micrograph of Figure 8, which also illustrates a typical fatigue spall. The dotted lines indicate the right hand edge of the contact zone where there are a number of cracks roughly paralleling the edge. These cracks slope away from the load zone into the body of the rod.

These cracks are recognized as being Hertz cracks[4,5,6] caused by the high compressive stresses employed in the RCF test and are analogous to the ring cracks which form in glass when it is indented with a hard sphere. This cracking phenomena was investigated further in the present contact by means of a dye penetrant* and scanning electron microscopy.

The rods used in the load-life testing (Table VI) were examined with the dye penetrant for incidence of cracking. When cracking was associated with a given load track, the cracking

*Penetrant Type ZL-22A, Developer Type ZP-9, Magnaflux Corp., Chicago, IL

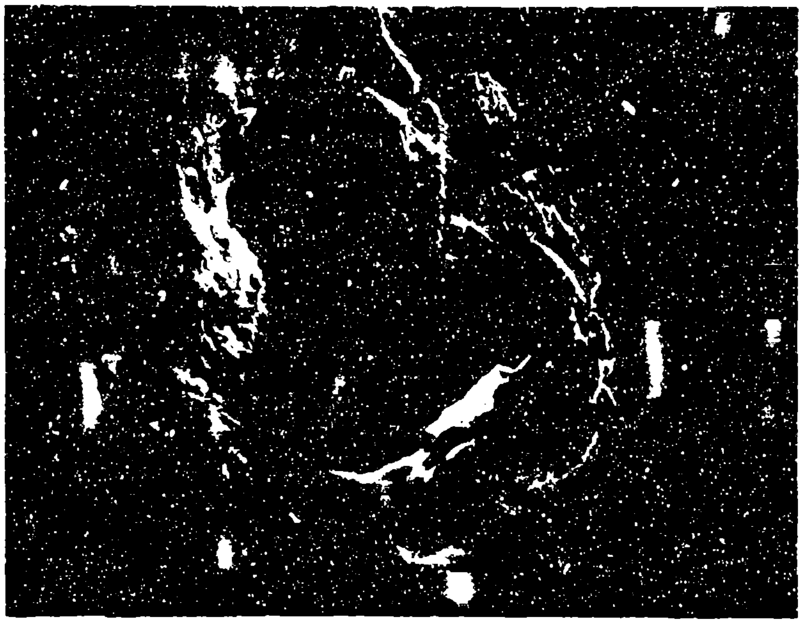


FIGURE 8 - Hertzian Cracks and Fatigue Spall on Rod 73-25, SEM, 100X.

was not always uniform; often one side of the contact zone was more severely cracked than the other. The results of the penetrant examination are summarized in Table IX.

Since all test failures are associated with spall formation, it is seen that strong correlation exists between Hertz crack incidence and spall formation. At the low 600 M psi stress level, all tests were suspensions and there were no failures or Hertz cracks, while at the 800 M psi level, all tests resulting in fatigue spalls and Hertz cracks. In no case did spalling occur without a Hertz crack also bordering the load track. At the intermediate loads, cracking was sometimes present even though spalls were not.

The suspended tests at the 700 M psi stress level sometimes did and sometimes did not exhibit Hertz cracks. Assuming that the penetrant was capable of detecting the Hertz cracks after a negligibly small number of stress cycles after their formation. it is concluded that the observed Hertz cracks require a large number of stress cycles to form, i.e. they are fatigue cracks.

The absence of any spalling or Hertz crack formation at the 600 M psi level and the connection between spalling and this

TABLE IX

Incidence of Hertzian Cracking and Spalling of RCF Rods

Stress Level (psi)	# of Tests	Condition at Test End
600 M		
	0	cracked with spall present
	0	cracked without spall present
	16	not cracked or spalled
	16	
700 M		
	8	cracked with spall present
	3	cracked without spall present
	5	not cracked or spalled
	16	
750 M		
	4	cracked with spall present
	2	cracked without spall present
	0	not cracked or spalled
	6	
800 M		
	11	cracked with spall present
	0	cracked without spall present
	0	not cracked or spalled
	11	

cracking (see below) leads to speculation that a threshold fatigue stress may be required for spalling which is in excess of the lowest stress level used in the RCF testing. If this speculation were correct, since the stress levels at which well designed actual bearings operate are well below that used in the 600 M psi level RCF tests, bearings made fully of silicon nitride would not normally be expected to fail by spall formation. If a fatigue limit and change in failure mode are not invoked, an extrapolation of the load-life calculation (Section II E2) gives an L_{10} at 600 M psi of about 1.5 billion cycles. For many practical applications, this life is equivalent to an infinite fatigue life.

The correlation between spalling and Hertz crack formation is not an unrelated coincidence. An examination of the spalls on this year's RCF rods by scanning electron and optical microscopy showed that a very large fraction of the spalls initiated from an associated Hertz crack. This conclusion was deduced from a) the asymmetrical location of the spall in the contact zone, abutting a crack, b) the contour of the bottom of the spall, which slopes into the bulk of the rod from a point on the surface at a Hertz crack, and c) the concentric circular fractographic markings which spread from the point of spall initiation and mark successive stages in the propagation of the fatigue crack of the spall. These markings may be seen in the spall of Figure 8. The approximate spall origin is marked with an O.

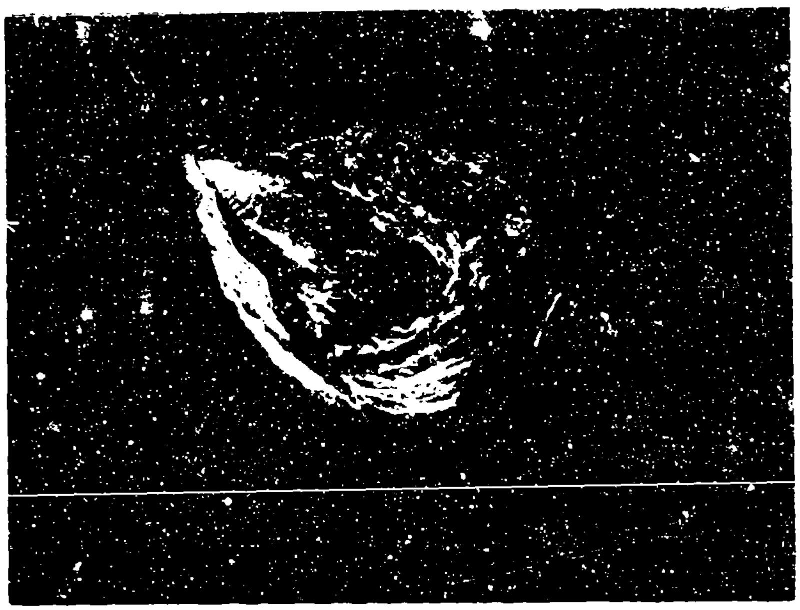


FIGURE 9 - Typical Fatigue Spall on Rod 73-17, SEM, 50X.

Figure 9 shows another example of a typical edge initiated spall. In this case Hertzian cracking is evident, often in the form of shallow arcs which do not penetrate far into the load zone. Figure 10 shows an example of a spall which is believed not to have initiated from the edge of the load zone, but rather from inside the zone near O and at the surface. Although not readily visible in the photograph, Hertz cracks were present nearby.

FIGURE 10 - Rare, Within Track Initiated Spall on Rod 73-9, SEM, 100X.

No inclusion was found to be associated the spall of Figure 10, nor with any spall origin on this material, through electron probing of the area of the o The rarity of spalls initiated inside the load track or at ons for the NC-132 silicon nitride rods is in contrast to eviously examined HS-110 silicon nitride rods[1]. This is ted to the greater microstructural uniformity of the NC-1 icon nitride.

The occurrence of the Hertzian cracking ex s the difficulty in obtaining fatigue spalls on the silicon c bide RCF rods during the 1972 contract work. At that time, the silicon carbide rods broke into two parts during fatigue testing before spalls formed. The lower fracture energy of silicon carbide, as opposed to silicon nitride, allowed the easier formation and propagation of Hertzian cracks. This, coupled with the higher modulus of elasticity of the silicon carbide, made the material more susceptible to rod fracture under the bending stresses caused by slight, but unavoidable, RCF test equipment misalignment.

Figures 11 through 16 show the appearances of the contact zones obtained on the RCF rods under a variety of test conditions. The appearances of the unloaded ground and lapped surfaces are given by Figure 2 and Figure 4, respectively. In general, loading produces wear which decreases the initial surface roughness and tends to obliterate the grinding scratches. This wear progress may be seen in the sequential series of Figures 2, 11 and 12 which show the initial ground surface and two later contact times at 800 M psi. During the early stages of wear, the highest and most severly disturbed material, which form the grinding scratches, is removed, leaving a pocked and imperfect peneplane (Figures 11, 13, 14 and 15). Longer times in contact with the steel loading wheels result in the break-up of the peneplane and the intergranular pull-out of silicon nitride grains. The silicon nitride wear debris is thus expected to be composed of grain-sized (1-2 microns) and smaller fragments. For steel loading wheels, as expected, wear at the 600 M psi stress level is slower than at the 800 M psi level, as may be seen by comparing Figures 13 and 12. At the 600 M psi level, the appearances of tracks made by steel (Figure 13) and silicon nitride (Figure 14) are quite similar. Somewhat surprisingly, the appearances of the silicon nitride loading wheel tracks at the 600 M and 800 M psi levels are very similar (Figures 14 and 15 respectively). The silicon nitride grain structure is especially evident in the wear track on the diamond lapped surface shown in Figure 16. The sub-micron white specks seen in Figures 11 - 16 are predominately small tungsten rich inclusions.

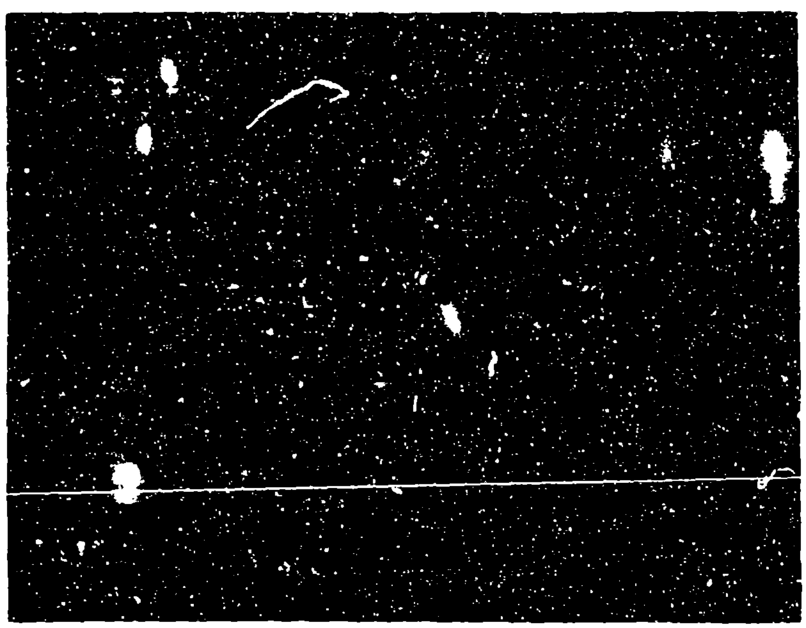


FIGURE 11 - Wear Track on Rod 73-17 After 2,840,000 Stress Cycles at 800 M psi; Steel Loading Wheels; SEM, 2000X.

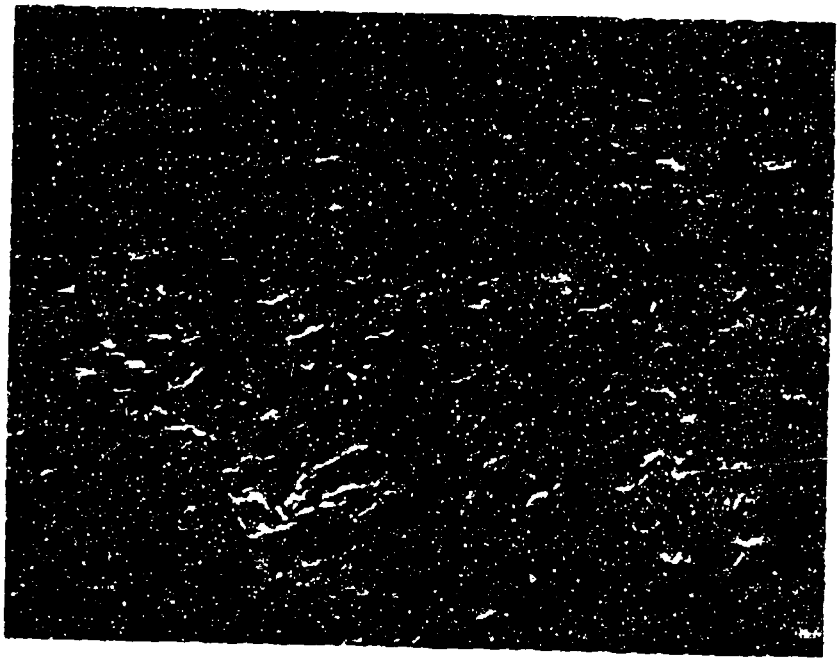


FIGURE 12 - Wear Track on Rod 73-10 After 9,460,000 stress cycles at 800 M psi, steel loading wheels, SEM, 2000X.

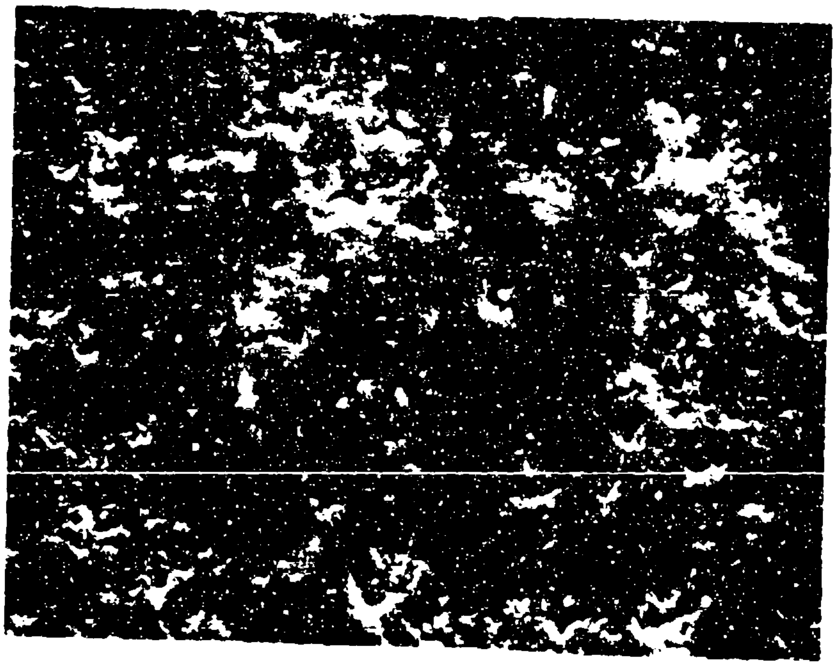


FIGURE 13 - Wear Track on Rod 73-10 After 63,480,000 Stress Cycles at 600 M psi, Steel Loading Wheels, SEM, 2000X.

FIGURE 14 - Wear Track on Rod 73-10 After 105,170,000 Stress Cycles at 600 M psi, Silicon Nitride Wheels, SEM, 2000X.

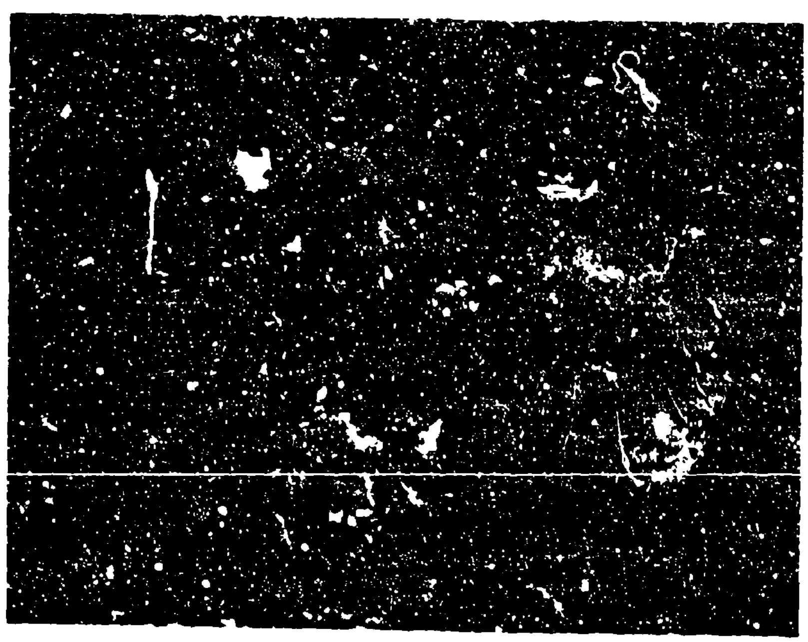


FIGURE 15 - Wear Track on Rod 73-9 After 45,780,000 Stress Cycles at 800 M psi, Silicon Nitride Wheels, SEM, 2000X.

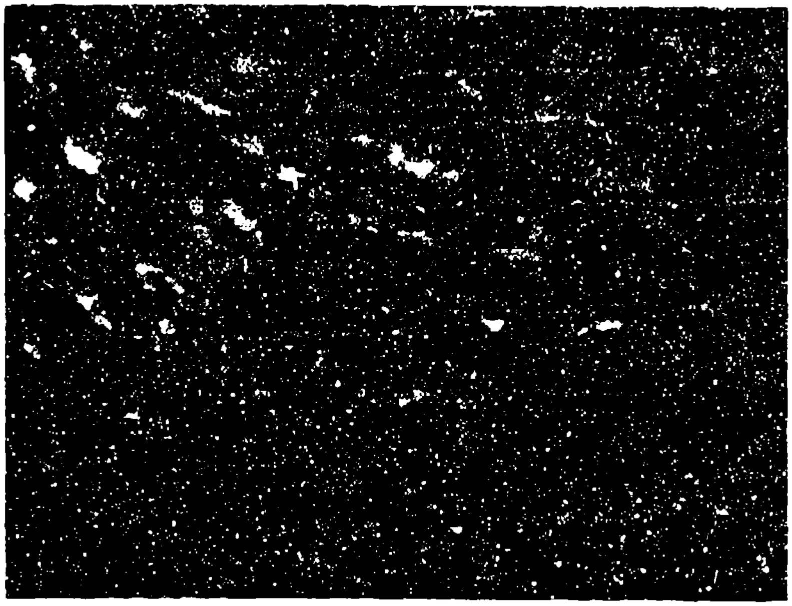


FIGURE 16 - Wear Track on Rod 73-25 After 3,700,000 Stress Cycles at 800 M psi, Steel Loading Wheels, SEM, 2000X.

2. Silicon Nitride Load Wheels

The crowns of the silicon nitride loading wheels were examined with the dye penetrant. The contact zone, around the entire circumference, was found to be covered with small Hertz cracks. Unlike the Hertz cracks on the RCF rods where the cracks formed in two parallel lines (as views on a macroscopic scale) on either side of the wear track, the cracks on the loading wheels were composed of short, arc segments which were discontinuous on the macroscopic scale. These cracks did not form a border to the contact zone, rather they curved into it. The different crack morphology is due to the different stress distributions in the cylindrical rod and the doubly curved crown. As a result of the cracks being present inside the load zone, the wheel spalls are believed to initiate directly from a Hertz crack, rather than branching from a pre-existant Hertz crack as was so often observed on the RCF rods. The way in which the cracks form is thus thought to contribute to the early failures of the silicon nitride load wheels.

Considering the number of stress cycles sustained, a given point on an RCF rod receives about thirty-seven (2 X wheel diameter/rod diameter) times the number of cycles in a given time as do the

loading wheels. Thus, other conditions being equal, the loading wheels would be expected to last, on the average, thirty-seven RCF tests. This was not the case. The major cause of the premature silicon nitride wheel failures is attributed to the finishing procedures used in their fabrication. A metal bonded 320 grit diamond wheel was used for the crown generation. It is now felt that the greater wheel grade hardness of the metal bond, combined with the greater friction of the metal bond-workpiece sliding couple, relative to a resinoid bond, lead to higher grinding stresses, both mechanical and thermal in origin. These higher stresses introduce greater sub-surface damage into the workpiece and reduce its strength. The consequence of the damage is easier Hertz crack formation and earlier spalling.

The much higher rate of wear debris generation with the use of the silicon nitride loading wheels is believed to be connected with the greater damage on the silicon nitride wheels (as contrasted to the silicon nitride rods). A higher density of microcracks or other sub-surface damage would result in a higher rate of wear particle formation. The removal, by wear, of this defective layer would result in a decreased rate of debris formation, as has been observed.

3. Wear Debris Analysis

The sample of black wear debris, obtained from the splash shield of the RCF machine after a silicon nitride on silicon nitride test, was submitted for x-ray diffraction analysis by the powder method. The first diffraction pattern showed no evidence of crystalline peaks, but was typical of an oil film. As no previous attempt had been made to remove the lubricant oil from the debris, an attempt to do so was made with acetone as the solvent. The second pattern was similar to the first. The absence of crystalline peaks is attributed to a residual oil film on the particles. The sample was not rewashed, to confirm the film hypothesis because the sample amount was already small and further washing would have resulted in a further particle loss.

A small sample of the debris, from which oil had been incompletely extracted was examined in the scanning electron microscope. Figure 17 shows larger wear particles while Figure 18 appears to be an oil-bonded agglomerate of very small particles. The particle sizes agree with that expected of wear particles from a ground silicon nitride surface as discussed in the previous section.

A qualitative electron probe analysis of the particles indicated the presence of silicon, nitrogen and carbon. The latter element presumeably originates from the carbon in the oil film.

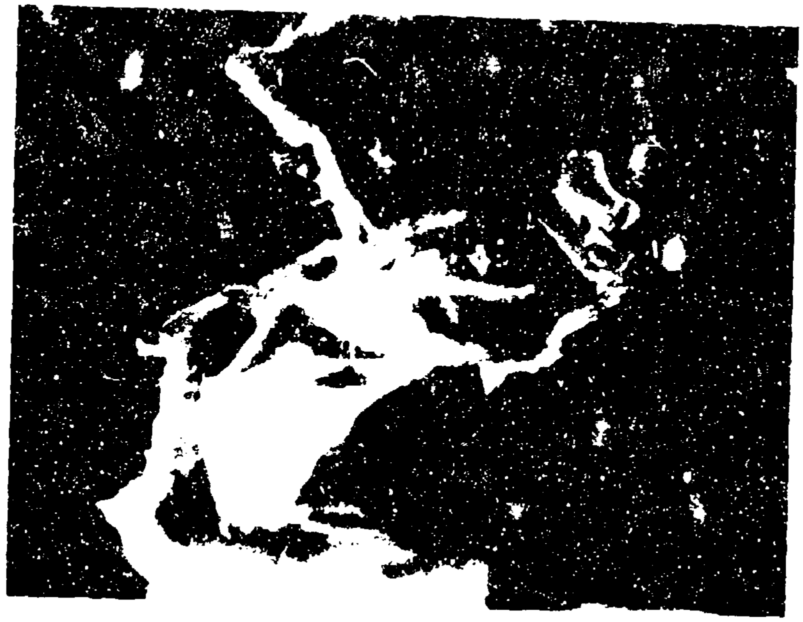


FIGURE 17 - Large Particle Silicon Nitride Wear Debris, SEM, 1000X.

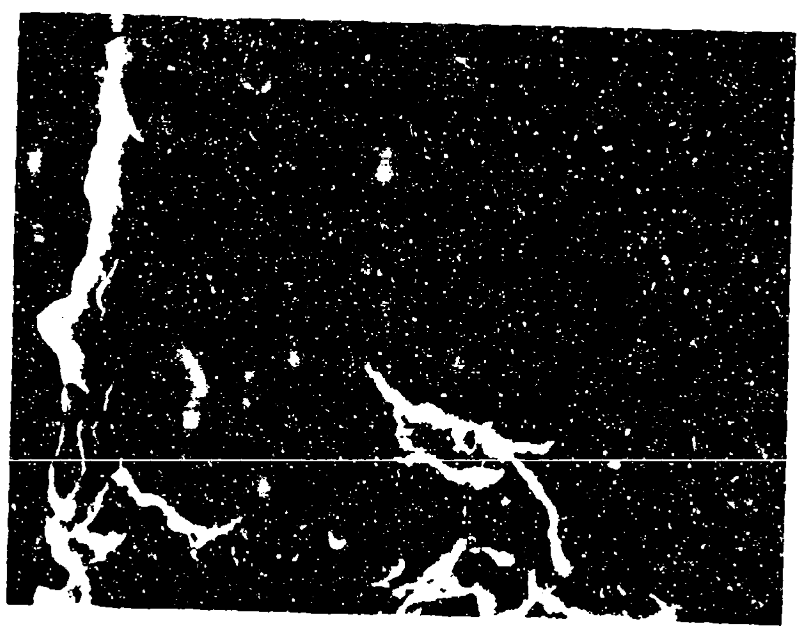


FIGURE 18 - Oil Bonded Agglomerate of Silicon Nitride Wear Debris, SEM, 1000X.

III. BEARING DESIGN AND FABRICATION

A. Silicon Nitride rollers with M-50 Steel Races

The design for the full bearing incorporating silicon nitride rollers, M-50 steel races, and AISI 4340 steel retainer is a modification of a Bower Aircraft bearing. The latter bearing was originally designed for use in an aircraft engine at the following conditions:

Radial Load:	265 to 380 lbs
Speed:	37,000 rpm
Temperature:	250°F to 400°F
Calculated Life:	10,000 hours to L_{10}

Besides the use of silicon nitride as the roller material, the modifications in the new design included the latest design criteria for high speed use. A primary reason for the use of silicon nitride rollers was to take advantage of their light weight to reduce the roller centrifugal force generated at high shaft speeds. With conventional steel rollers, the outer race can experience early fatigue failure due to high centrif loading. The silicon nitride roller-steel race bearing was designed to run at speeds up to 65,000 rpm and under radial loads up to 400 pounds. A drawing of the bearing assembly is shown in Figure 19 and a roller drawing is shown in Figure 20.

The fabrication of the M-50 CVM steel races and the AISI 4340 steel retainers was complete in 1972 except for final race track dimensions. However, in the previous contract period, the rollers fractured during end grinding and the bearing test phase of the program was inserted into the 1973 contract period. Fabrication of races and retainers proceeded without incident and the dimensions are within tolerance limits. Table X gives some dimensional characteristics of the races compared to the specifications. Table XI gives the dimensional characteristics of the silver plated retainers.

The NC-132 silicon nitride roller stock was qualified as covered in Section II E1. The fabrication of the silicon nitride rollers was accomplished in two phases. The first phase proceeded by the following steps: Bar stock, 6" x 7/16" x 7/16", was taken from a square to round cross section with a 120 grit diamond, resinoid bonded wheel on an O.D. grinder. The rods were reduced in diameter on a centerless grinder, employing a 220 grit diamond, resinoid bonded wheel. A total of approximately 0.030 inch was removed in steps and the wheel allowed to run-out on the final passes. A hand held, cast iron ring lap was used to remove a maximum of 0.0002 inch while the rod rotated in a chuck at 200 rpm.

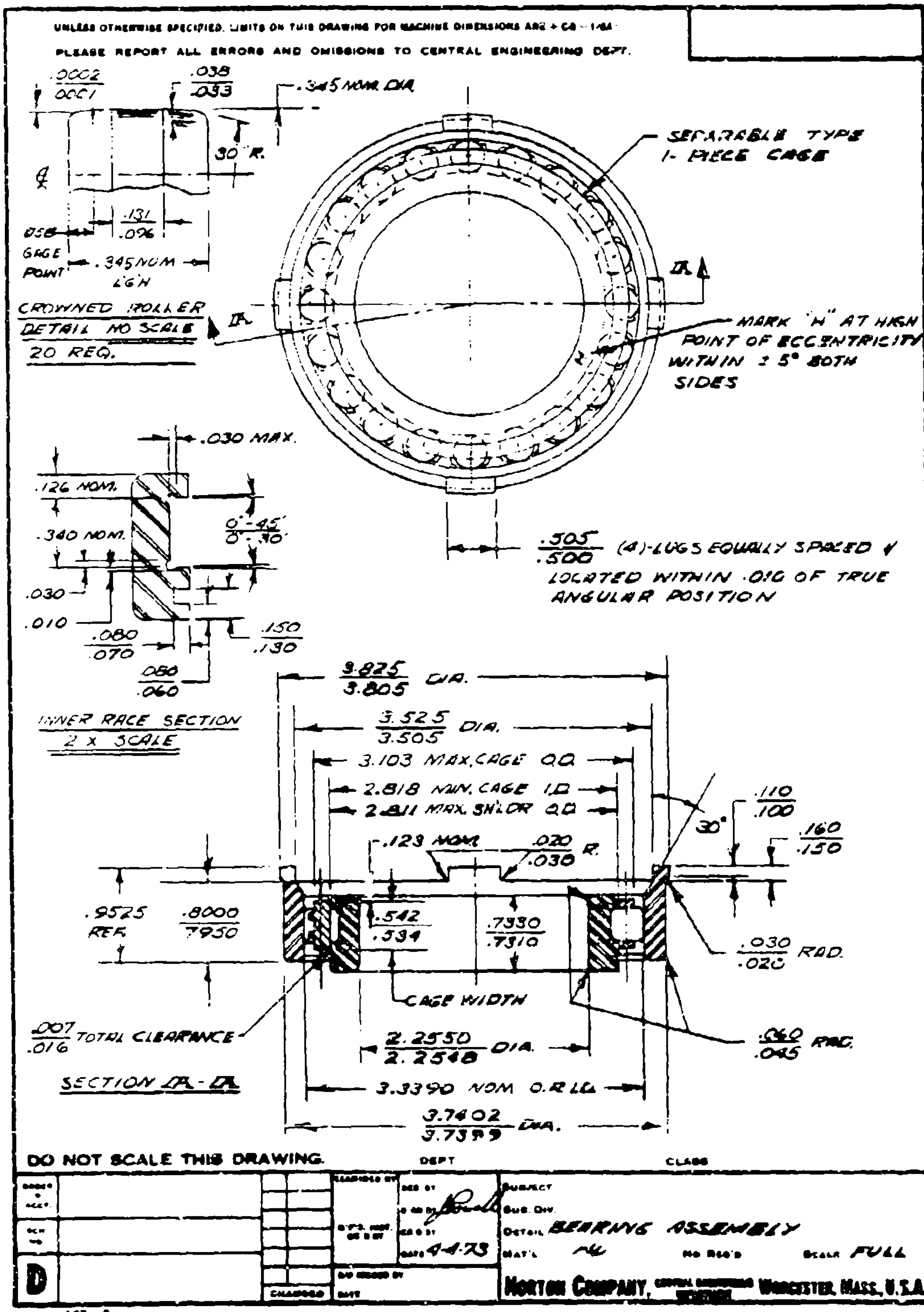


FIGURE 19 - Design for Bearing with Steel Races and Silicon Nitride Rollers.

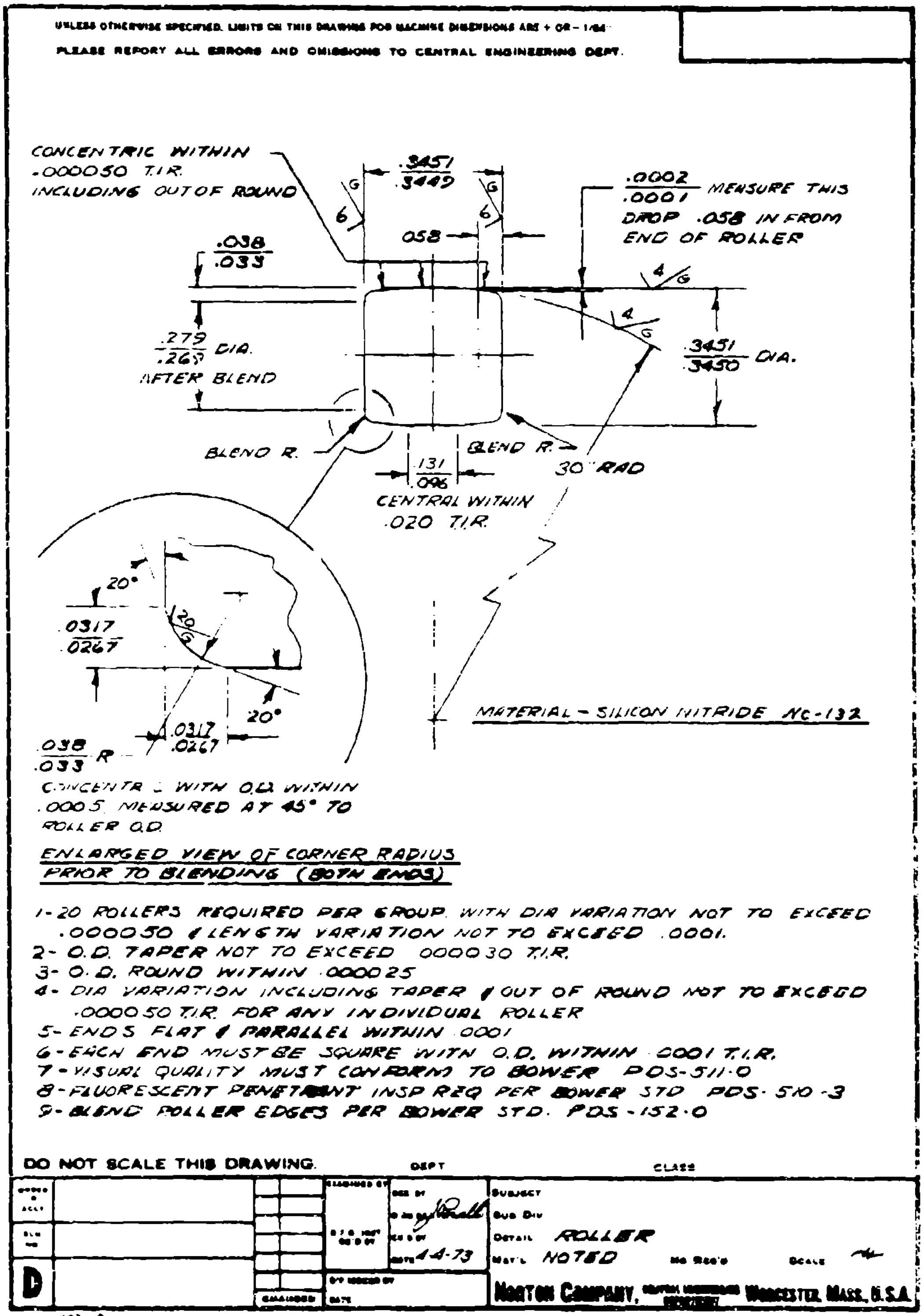


FIGURE 20 - Silicon Nitride Roller Design

TABLE X

Dimensional Characteristics of M-50 CVM Bearing Races

Inner Races

Attribute	Specification(1)	#1	#2	#3
O.D. Track	2.6466/2.6461	2.6461	2.6461	2.6460
Out-of-Round	0.000050 max.	0.000025	0.000025	0.000025
O.D. Taper	0.000050 max.	0.000025	0.000020	0.000025
O.D. Surface Finish	6AA max.	4 AA	4 AA	6 AA
I.D. Bore	2.2550/2.2548	2.25485	2.25485	2.25485
Out-of-Round	0.0001 max.	0.000050	0.000075	0.0001
I.D. Taper	0.0001 max.	0.0001	0.0001	0.0001
I.D. Surface Finish	16 AA max.	12 AA	14 AA	10 AA
I.D./O.D. Concentricity	0.00015 max.	0.0001	0.0001	0.0001
Track Width	0.3464/0.3459	0.34615	0.3461	0.3459

Outer Races

Attribute	Specification	#1	#2	#3
I.D. Track	3.3395/3.3390	3.3392	3.3392	3.3394
Out-of-Round	0.0001 max.	0.000050	0.000050	0.000050
I.D. Taper	0.000050 max.	0.000050	0.000150	0.000075
I.D. Surface Finish	6 AA max.	6 AA	6 AA	6 AA
O.D.	3.7402/3.7399	3.74005	3.74005	3.7401
Out-of-Round	0.000050 max.	0.000050	0.000050	0.000050
O.D. Taper	0.000050 max.	0.000050	0.000050	0.000050
O.D. Surface Finish	16 AA max.	10 AA	10 AA	10 AA
I.D./O.D. Concentricity	0.0-035 max.	0.00050	0.00050	0.0001

(1) All dimensions in inches.

TABLE XI

Dimensional Characteristics of AISI 4340 Steel Retainers

Attribute	Print Specification (1)	#1	#2	#3	#4	#5	#6
Before Silver Plate:							
O.D. Side A	3.097/3.092	3.0930	3.0920	3.0915	3.0920	3.0950	3.0950
O.D. Side B	3.097/3.092	3.0925	3.0920	3.0918	3.0925	3.0940	3.0950
I.D. Side A	2.826/2.822	2.8235	2.8240	2.8242	2.8240	2.8240	2.8240
I.D. Side B	2.826/2.822	2.8235	2.8240	2.8242	2.8240	2.8235	2.8243
Pocket Width	0.3681/0.3651	All Within Limits					
Pocket Height	0.3648/0.3618	All Within Limits					
After Silver Plate:							
I.D.	2.818 min.	2.8215	2.8217	2.8220	2.8220	2.8218	2.8214
O.D.	3.103 max.	3.0952	3.0945	3.0940	3.0940	3.0960	3.0945
Clearance	0.016/0.007	0.0106	0.0108	0.0112	------	------	------

(1) All dimensions in inches.

Lapping paste of six to nine micron diamond was used. The individual roller blanks were sliced from the longer rods. The blank ends were squared on a surface grinder using a 120 grit diamond, resinoid bonded wheel and left in an oversize condition. The corner radii were then generated in a special fixture attached to a surface grinder, using the latter type wheel. A hand lapping operation with nine micron diamond paste was used to polish and blend-in the corner radii. The blank lengths were brought to final size on a face lapping machine with six to nine micron diamond paste. In the final finishing operation of the first phase, a disc lapping machine was used to produce the desired blank diameter. Six micron diamond paste was used to remove approximately 0.0004 inch off the blank diameter. Two hundred roller blanks were produced by the above procedure. One hundred twenty-six were produced to the tolerances required; the remainder were out of tolerance on the attribute of end squareness. Table XII shows the measured dimensions compared to the print tolerances.

TABLE XII

Dimensions of Silicon Nitride Roller Blanks

Attribute (inch)	Print Specification	Received*
Diameter	0.34570/0.34550	0.34564/0.34562
Length	0.34510/0.34500	0.34508/0.34507
End Squareness	0.0001 max. T.I.R.	0.000300/0.000020
Corner Radius Runout	0.0005 max. T.I.R.	0.00045/0.0001
O.D. Taper	0.000030 max. T.I.R.	0.000025/0.000020
Out-of-Round	0.000025 max. T.I.R.	0.000015/0.000008
End Parallelism	0.0001 max. T.I.R.	0.0002/0.000050

*Based on a 10 roller sample except for end squareness where 200 were measured.

The second phase of roller fabrication was accomplished at the Federal Mogul Aircraft Bearing Plant. This phase consisted of plunge grinding the crown and flat on the roll with a glass bonded wheel of 150 grit, friable silicon carbide abrasive. Since generation of the final roller shape with a diamond wheel on 200 rollers is economically not feasible, at the present state of the art, conventional silicon carbide crowning was employed. During last year's contract work, it was shown that the removal of a less than 0.001 inch thick surface layer with a silicon carbide wheel did not

adversely affect rolling contact performance. A maximum of 0.0004 inch and 0.0005 inch were removed from the roller surface at the central flat and shoulder, respectively, by the silicon carbide grinding.

Tapering of the flat portion of the K crown during silicon carbide grinding was experienced. This was detected during grinding and was minimized by set-up procedure. Some tapering, however, occurred at unpredictable times during the grinding. Proficording of a fifteen piece sample showed the crown taper exceeded the 30 millionths of an inch limit on eight of the pieces, the highest measured taper being 100 millionths of an inch. Figures 21 and 22 are linear proficordings of roller crowns with acceptable and non-acceptable taper, respectively. Tapering of this degree is not normally encountered when grinding steel rollers of similar size with a silicon carbide wheel. However, since more experience has been generated with the grinding of steel rollers than with silicon nitride rollers, the residual difficulty may well be removed by further improvements in set-up procedure and wheel selection.

After final finishing, the 200 original roller blanks were accounted for in the following manner:

120 - six groups of twenty sized to 0.000050" diameter variation.

23 - crowned but out of tolerance on end squareness.

34 - set up pieces and visual rejects.

17 - unground - out of tolerance on end squareness

6 - unaccounted

200 - TOTAL

A sampling of the 120 finished and sized blanks was made for diameter and specific crown characteristics (see Table XII). A typical rotary proficording of a sample roller is shown in Figure 23. Overall, the rollers are to print tolerances with the exception of the maximum diameter variation within a group of 20 rollers and crown flat taper. The diameters are measured at the center of the roller lengths. Within one group, the diameter of two rollers differ by as much as 115 millionths of an inch from the low diameter of one to the high diameter of the other. However, if the average diameters of each respective roller are considered, the maximum variation is within the 50 millionths of an inch allowed.

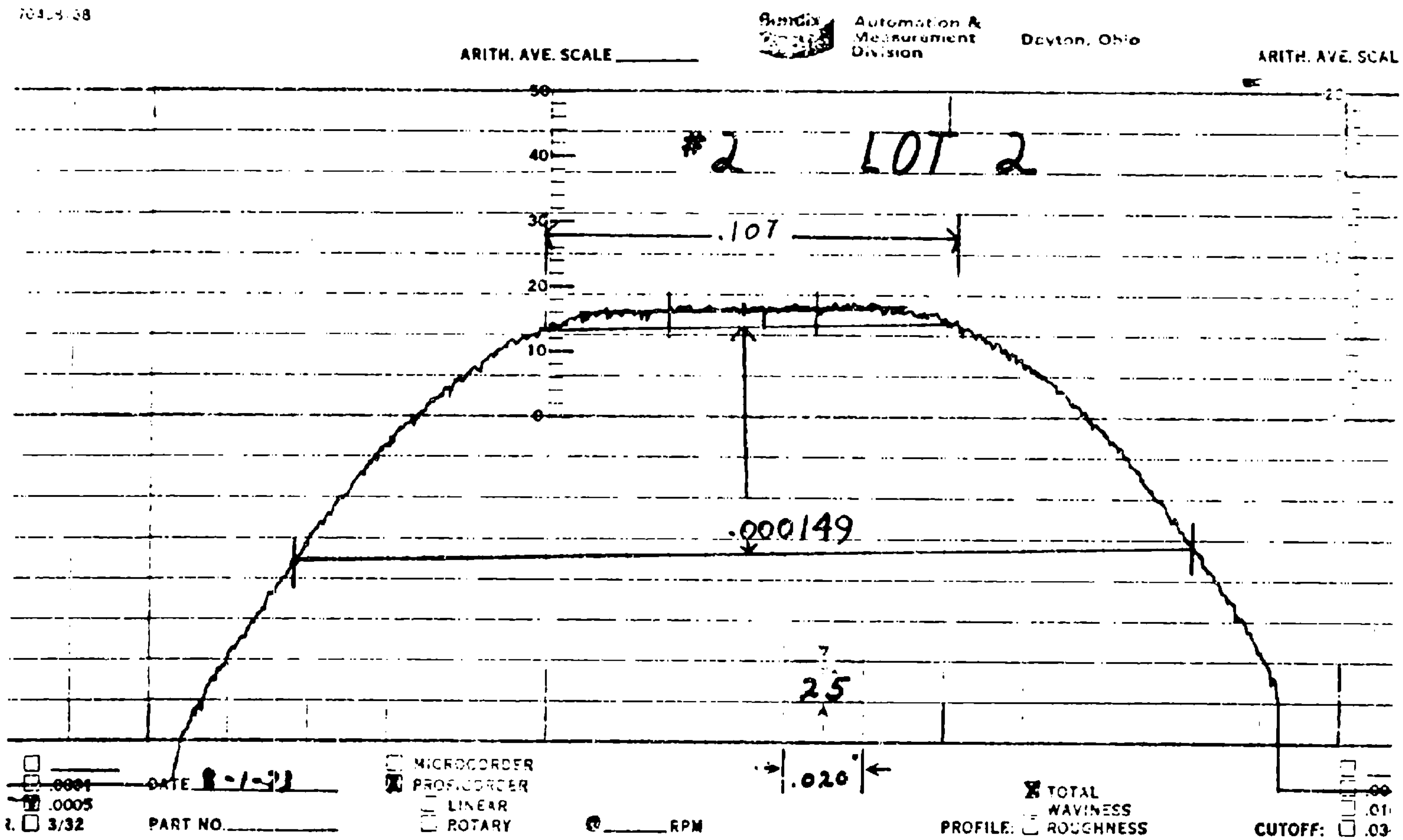


FIGURE 21 - Linear Proficorder Trace Across a Silicon Nitride Roller (Acceptable Contour).

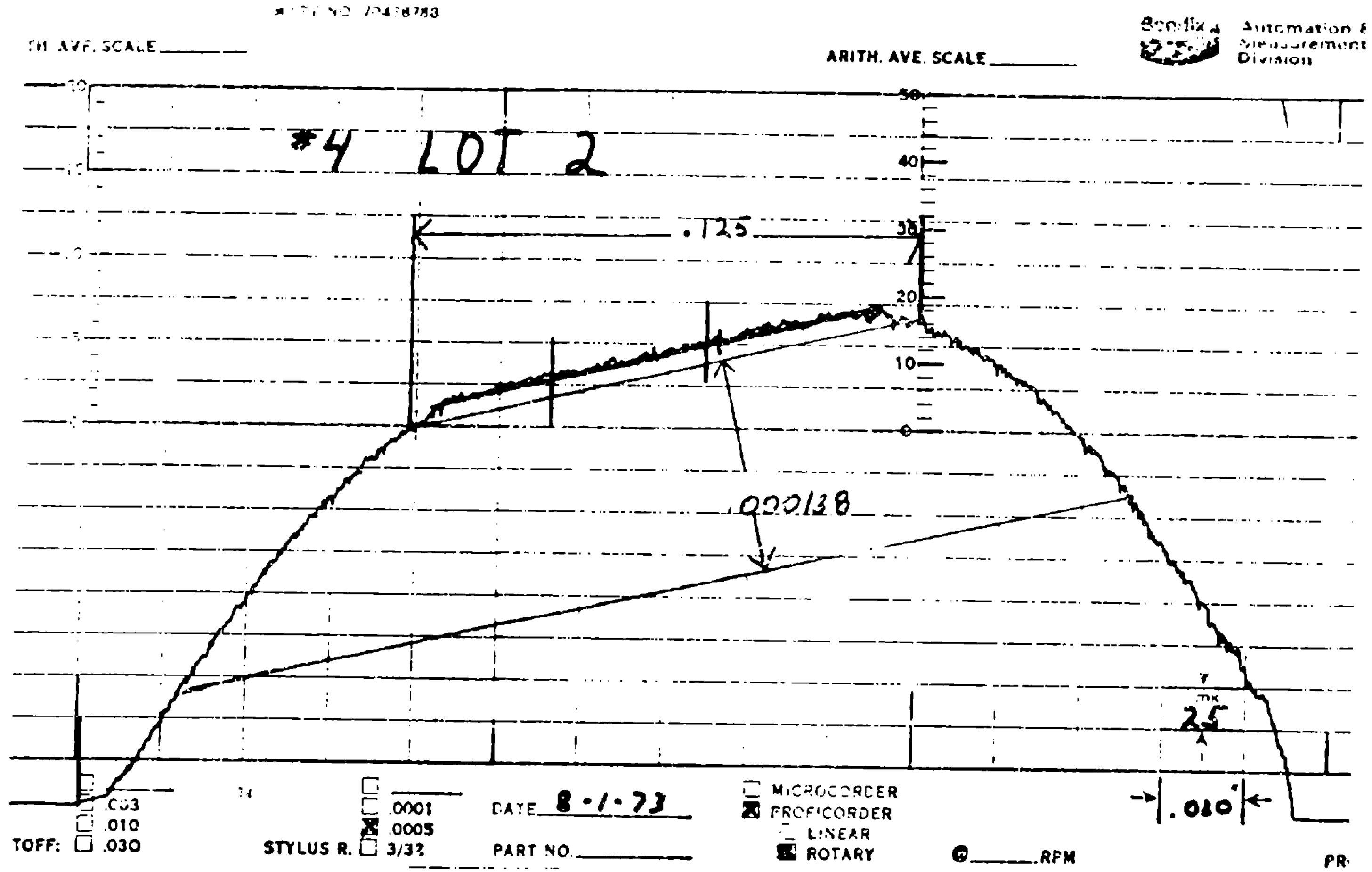


FIGURE 22 - Linear Proficorder Trace Across a Silicon Nitride Roller (Unacceptable Contour).

TABLE XIII

Silicon Nitride Finished Roller Crown Dimensions

Attribute	Print Specification	Received*
Out-of-Roundness,in.	0.000025 max. T.I.R.	0.000065/0.000020
Max.Diameter Variation Within 20 Roller Group, in.	0.000050 max. T.I.R.	0.000115/0.000085
Flat Length, in.	0.131/0.096	0.120/0.098
Crown Height, in.	0.0002/0.0001	0.000155/0.000128
O. D. Taper, in.	0.000030 max. T.I.R.	0.000100/0.000000**

*Measured 60 of the 120 rollers and expressed in range extremes

**Measured 15 of the 120 rollers

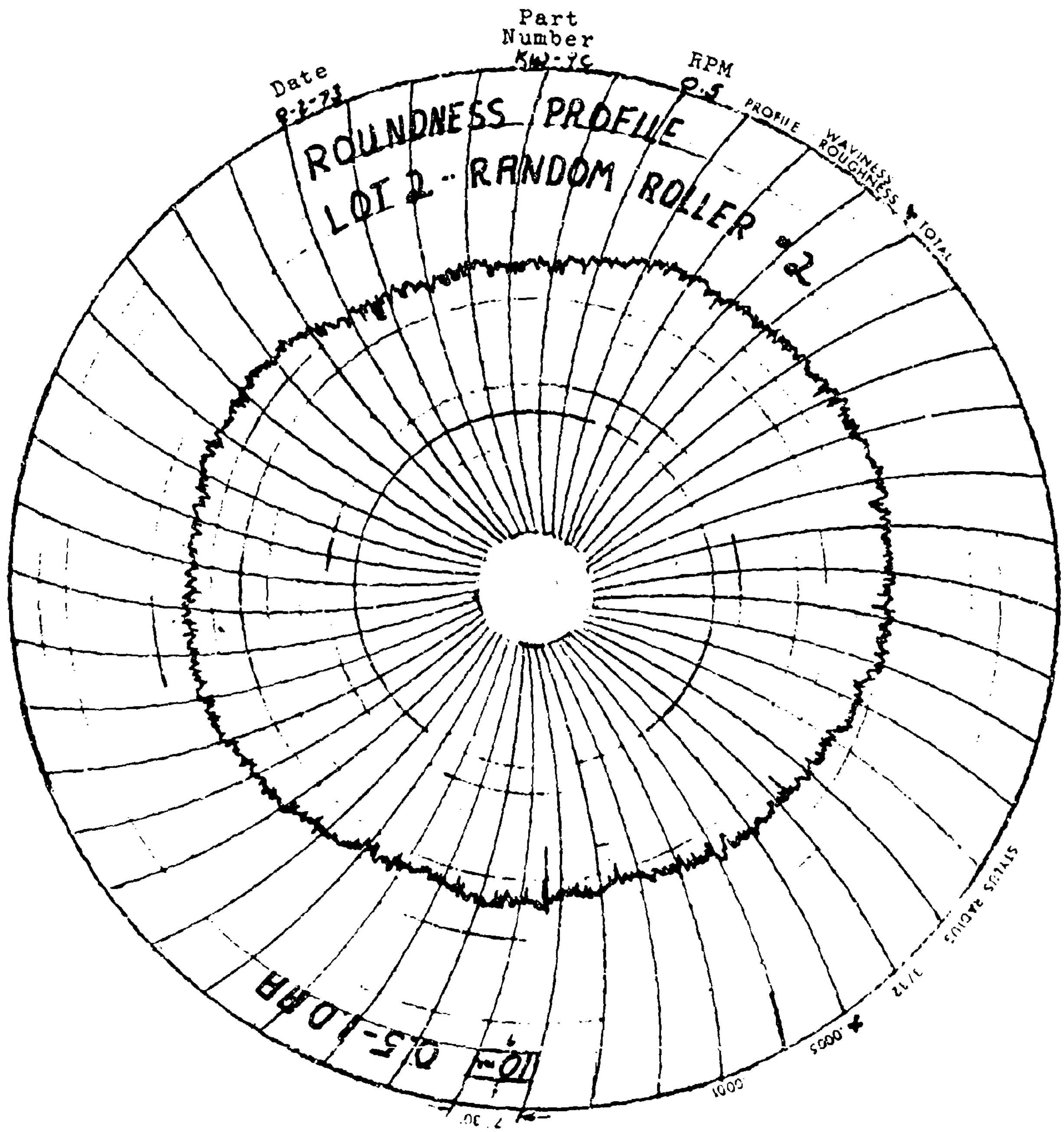


FIGURE 23 - Rotary Proficording of a Typical Finished Silicon Nitride Roller

Figure 24 shows the finish on a silicon carbide ground surface. The smooth regions are characteristic of this finishing. The material's microstructure may be seen in the rougher regions.

FIGURE 24 - Surface of Silicon Carbide Ground Roller, SEM, 2000X.

The races, retainers and the sized-grouped rollers were assembled to make three complete bearings, serialized A-1, A-2 and A-3 and are shown in Figure 25. A close-up of one bearing is shown in Figure 26. The measured diametral clearances of the assemblies were from 0.0025" to 0.0028", within the specification of 0.002" to 0.003".

B. Silicon Nitride Rollers and Silicon Nitride Races

The design of the silicon nitride races was patterned after the above described steel race design in order to use similar rollers and retainers. The assembly drawing is shown in Figure 27. Basic differences between the steel and the silicon nitride races are the elimination in the ceramic design of the inner race puller groove and the outer race anti-rotation tangs.

The method of inner race attachment to the shaft was also modified. The conventional bearing mounting technique with inner race rotation is to use a press fit to prevent the inner race from

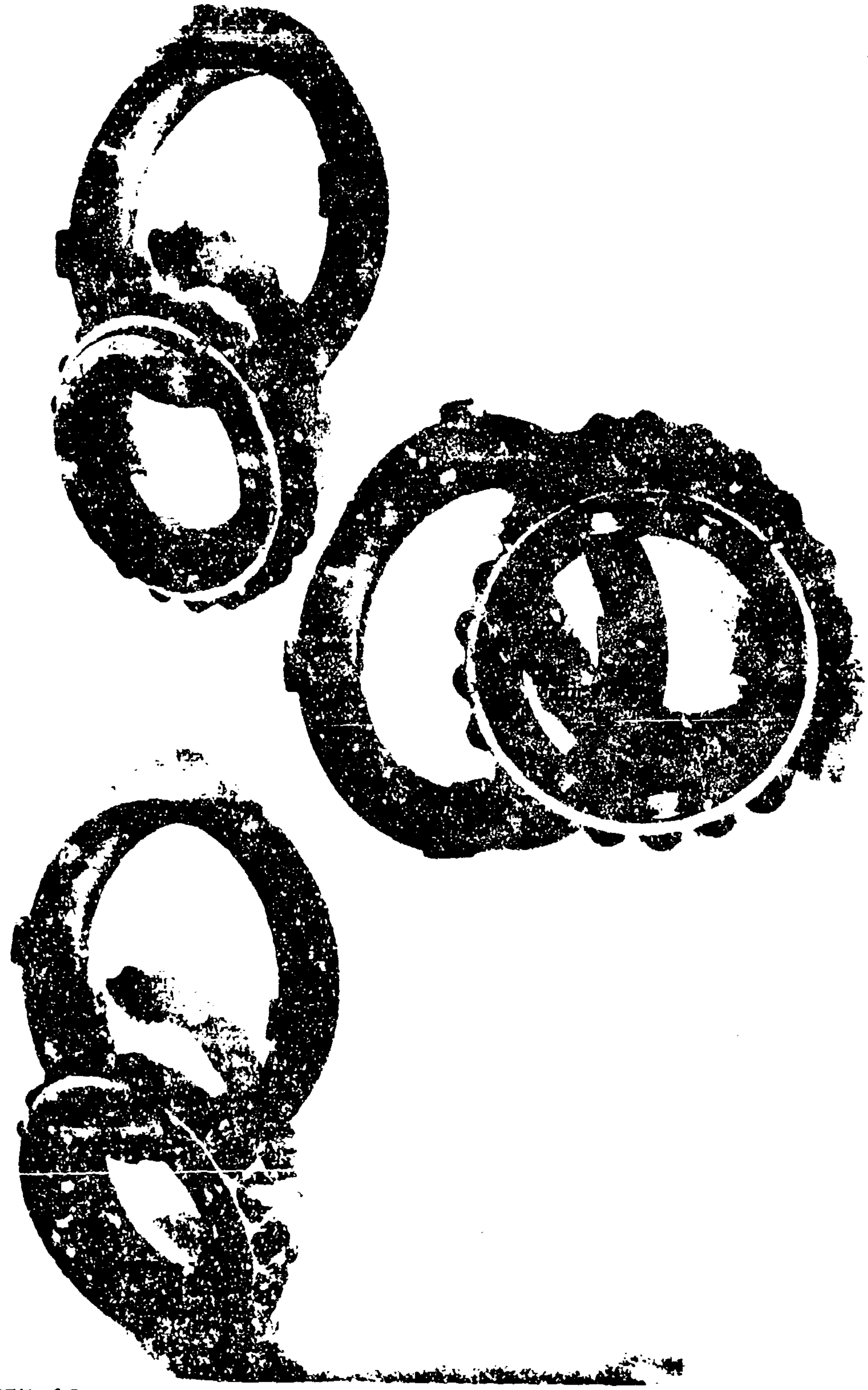


FIGURE 25 - Assembled Bearings with Silicon Nitride Rollers and M-50 CVM Steel Races.

FIGURE 26 - Bearing Containing Silicon Nitride Rollers and Steel Races.

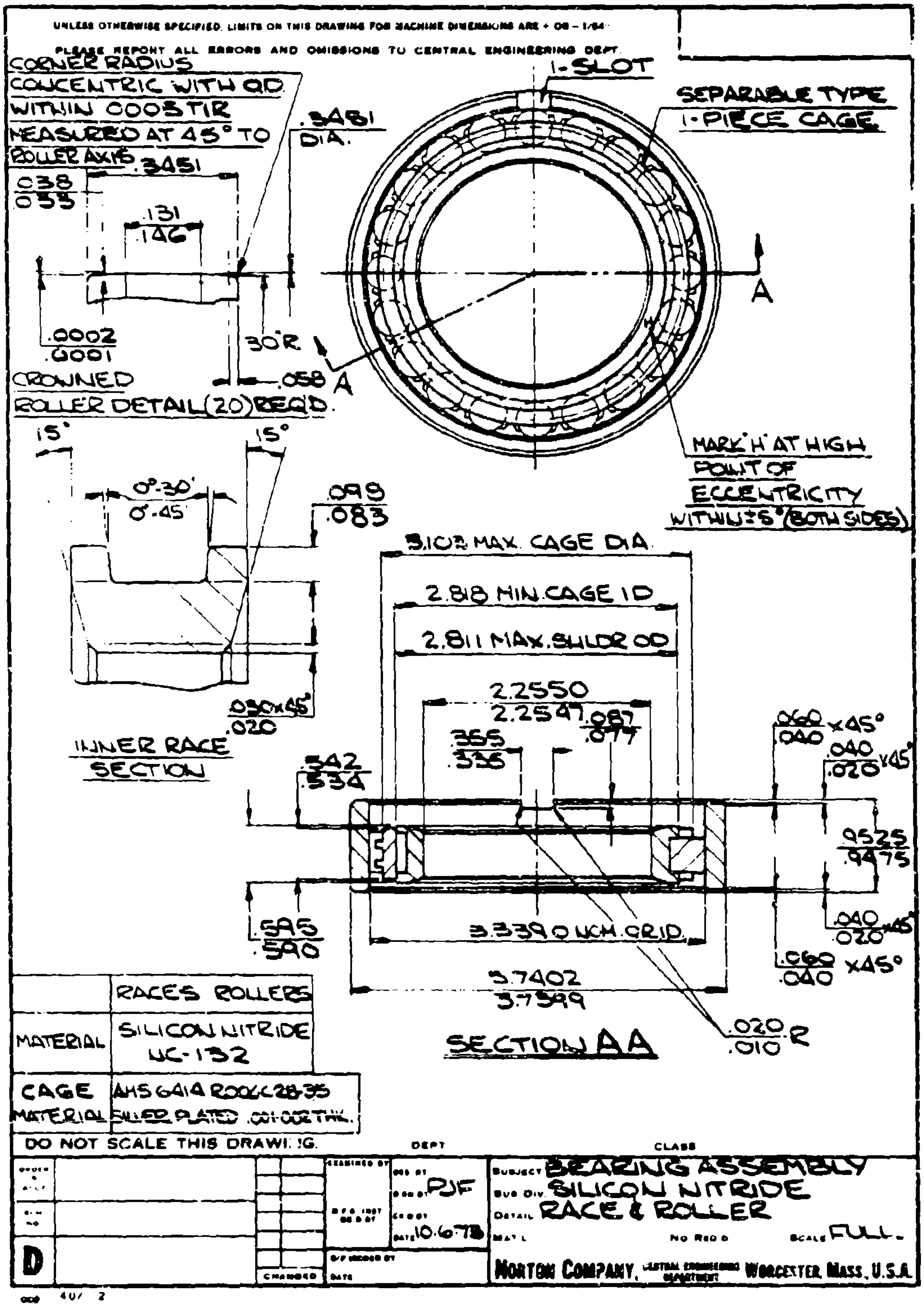


FIGURE 27 - Silicon Nitride Bearing Assembly

turning on the shaft. With a silicon nitride race (coefficient of thermal expansion $1.77 \times 10^{-6}/°F$) and a steel shaft (coefficient of thermal expansion $6.5 \times 10^{-6}/°F$) the interference fit would increase due to the shaft expansion. An increase in fit would increase the inner races hoop stresses, possibly reduce fatigue life, and may eventually fracture the race. In order to prevent this condition from occurring a mounting scheme shown in Figure 28 was employed.

The inner race is axially clamped into position by torquing the retaining nuts. A loose fit of 0.0003 to 0.0007 inch exists for the support ball bearings and clamping collars. The inner race fit of 0.0011 to 0.0016 inch loose will result in a line to line to 0.0005 inch tight fit at an operating temperature of 175°F. The axial clamping force is maintained by the clamping collar with an angled face to match the face angle of the inner race. As the shaft expands axially, the radial expansion forces the collar against the inner race face, holding it in position. The race face and collar angle is calculated, based on the difference in axial and radial expansion of the race and shaft.

The fabrication and assembly of the ceramic roller bearings used groups of silicon nitride rollers described previously and retainers from the same group that have also been described. The silicon nitride races were produced from NC-132 silicon nitride annuli of dimensions 3" OD X 2-1/16" ID X 3/4" thick for the inner races and 4" OD X 3-1/8" ID X 1-1/16" thick for the outer races. The inside diameters of the outer races were ground with a 270-320 diamond grit, metal bonded wheel on an ID grinder. The outer diameter groove of the inner race was ground with a formed, 320 diamond grit, metal bonded wheel on an OD grinder. All grinding was done wet at 5000 sfpm. Machine feeds were dependent upon wheel condition and ranged from 0.001 to 0.0001 inch per work stroke, the latter feed being used near final sizing. The final finish of the inner race groove was done by holding, by hand, a flat piece of hard brass against the rotating race. Between 0.0003 to 0.0004 inch was removed in this way with three micron diamond paste.

Table XIV gives a dimensional analysis of the races compared to specifications. Dimensional tolerance and surface finish are considered good with the exception of race track taper. However, it is felt that with sufficient time available, the off-taper condition could have been corrected.

Three bearings with silicon nitride races and rollers were fabricated with AISI 4340 steel retainers and are shown in Figure 29. A close-up is shown in Figure 30. The bearings are serialized 1, 2 and 3. The measured diametral clearances of the three were within the tolerance range of 0.001 to 0.002 inch.

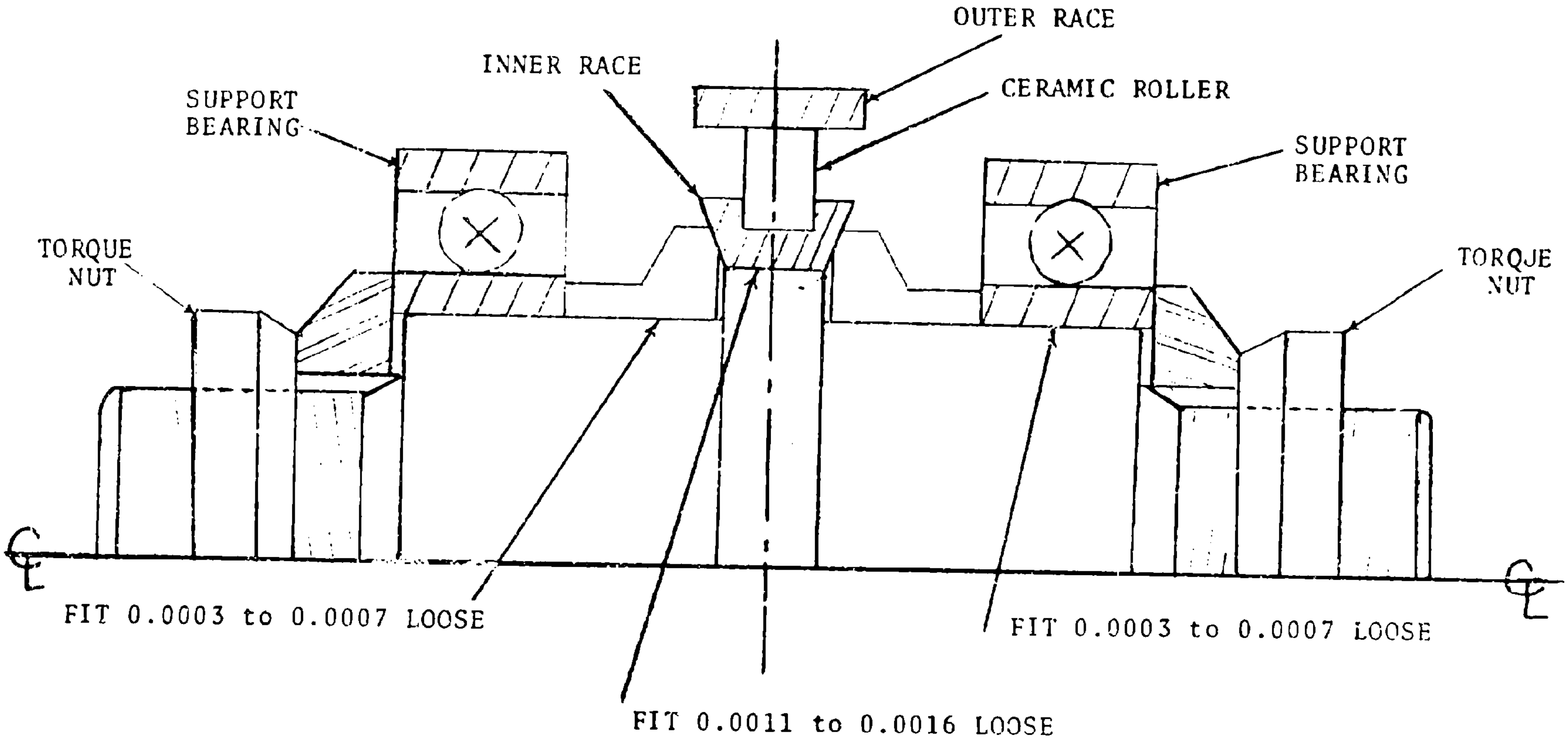


FIGURE 28 - Method Used to Hold Ceramic Race to Shaft

TABLE XIV

Dimensional Characteristics of Silicon Nitride Bearing Races

Inner Races

Attribute	Specification(1)	#1	#2	#3
O.D. Track	2.6466/2.6461	2.6462/2.6461	2.6465/2.6464	2.6462/2.6461
I.D.	2.2550/2.2547	2.2550/2.2548	2.2550/2.2548	2.2550/2.2549
Track Width	0.3464/0.3459	0.3457*	0.3455*	0.3459
Raceway Taper	0.000050 max.	0.000040	0.000050	0.000090*
I.D./O.D. Concentricity	0.00015 max.	0.00006	0.00018	0.00008
Raceway Surface Finish	6 AA max.	5.5 AA	7 AA*	2 AA
O.D. Track Out-of-Roundness	0.00025 max.	0.000030	0.000050	0.000050

Outer Races

Attribute	Specification(1)	#1	#2	#3
O.D.	3.7402/3.7399	3.7402/3.7400	3.7403/3.74015	----
I.D. Track	3.3390 nominal	3.33835/3.33814	3.33856/3.33806	----
I.D./O.D. Concentricity	0.00015 max.	0.00022*	0.00022*	0.00022*
Raceway Taper	0.000050 max.	0.000130*	0.000250*	0.000130*
Raceway Surface Finish	6 AA max.	6 AA	6 AA	---
I.D. Track Out-of-Roundness	0.00025 max.	0.000090	0.000080	---

* Exceeds tolerance limits

(1) All dimensions in inches

FIGURE 29 - Bearings with Silicon Nitride Rollers and Races

FIGURE 30 - Bearing with Silicon Nitride Rollers and Races

IV. TESTING OF BEARINGS

A. Description of Equipment

The equipment used to test the assembled bearings, both steel-ceramic and ceramic-ceramic, is shown in Figure 31. It has the capability of applying 4,000 pounds radial load to a test assembly and a shaft speed range to 10,000 rpm. The test head is equipped with accelerometers which detect both high and low vibration levels and can be set to stop the test when the "noise" level goes below or above set values. Thermocouples are also placed in the test head to measure both test bearing and support bearing outer race temperatures.

B. Test Conditions

The load, speed, temperature and lubricant were held constant for both the steel-ceramic and ceramic-ceramic bearings. These conditions are outlined below:

Load: 500 lbs. to 2500 lbs. radial

Speed: 1200 to 10,000 rpm

Temperature: 170°F to 190°F

Lubricant: Enco 2380 Type II Turbo Oil (MIL L-23699B) 10 micron filter system.

These are accelerated test conditions and were chosen to simulate the high outer race stresses in a high speed bearing by increasing the load above design load.

The calculated nominal maximum Hertz compressive stresses for a number of the load conditions used are given in Table XV.

TABLE XV

Calculated Maximum Hertz Compressive Stresses for Test Bearings

Radial Load Lbs.	Nominal Maximum Hertz Compressive Stress, psi		
	Steel-Steel	Steel-Silicon Nitride	Silicon Nitride-Silicon Nitride
500	147,000	162,000	184,000
1000	193,000	212,000	241,000
1200	208,000	228,000	259,000
2500	283,000	310,000	351,000

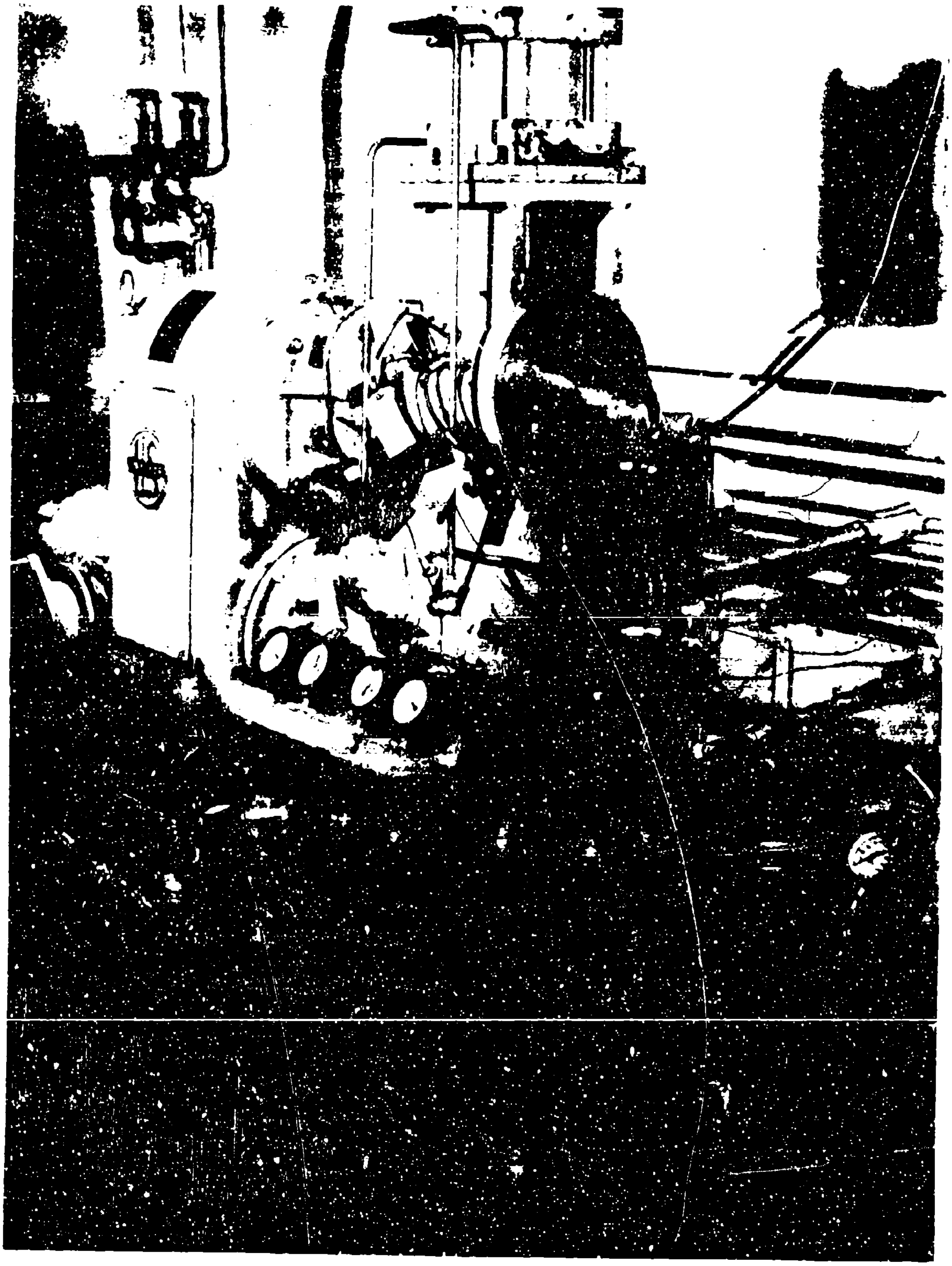


FIGURE 31 - Variable Speed Bearing Test Machine

These take into account the bearing geometry including diametrical clearance and roller crown profile. Note the increase in stress at constant load due to the high modulus of elasticity (45×10^6 psi) of silicon nitride. The majority of the testing was under the accelerated load of 2500 pounds and at 10,000 rpm. The AFBMA calculated life (Appendix III) at the L_{10} rank (10% of the bearings will fail in less time) for a bearing made of steel and run under these conditions is 120 hours. An estimate of the mean life (L_{50} rank) would be approximately 475 hours.

C. Test Results - Steel Races and Silicon Nitride Rollers

Two of the three bearings fabricated were tested under accelerated conditions without fatigue failure or unusual wear. The third was not tested. The test set up is shown in Figure 32. The bearings were suspended from test after 76 hours and 640 hours at 10,000 rpm and 2500 pounds load. A detailed load-speed-temperature accounting is shown in Table XVI. The bearing serialized as A-2 is shown in Figure 33 after 641 hours of operation. The outer race load zone shows that edge loading occurred during test. The amount is shown in Figure 34 by the linear proficording across the track. The edge wear of 125 millionths of an inch occurred due to the outer race test adapter deflecting under load, allowing the outer edges of the roller to contact instead of just the crowned portion. The race taper evident in Figure 34 is within print specifications and appears magnified due to the choice of scale. The taper did not cause the edge loading. The Hertz compressive stress due to this roller edge loading was in excess of the 310 M psi calculated value, but this did not cause a fatigue failure. Diametral clearance remained within print specifications after suspension, indicating that the overall wear (races plus rollers) was not excessive. Both bearings finished testing in excellent condition and could have been tested further.

Figure 35 shows the surface of a roller from the A-2 bearing after test suspension. A comparison with Figure 24 shows that very little wear of the silicon nitride has occurred, as indicated the the continued existance of the smooth features of the original condition. The white specks in the figure are tungsten rich inclusions. There was negligible iron pick-up on the silicon nitride surface.

After test, the inner web surfaces of the retainer were covered with a dark residue. A sample of this residue was stripped with plastic replicating tape and is shown in Figure 36. The residue is composed of wear particles of iron from the steel races. No significant silicon peak, which would have indicated the presence of silicon nitride wear particles, was found.

FIGURE 32 - Bearing Test Adapters and Steel Race Bearing

TABLE XVI

Test Conditions: Steel Races - Silicon Nitride Rollers

Bearing Number	rpm	Load Lbs.	Temp. °F	Time Hrs.	Total Time Hours
A-1	1,200	500	175	0.8	0.8
	2,400	500	175	0.5	1.3
	3,600	500	175	3.2	4.5
	5,400	500	172	18.4	22.9
	10,000	500	175	21.7	44.6
	10,000	1000	178	100.1	144.7
	10,000	2500	198	76.1	220.8
					No Failure
A-2	5,400	1500	172	0.9	0.9
	10,000	2500	172 - 189	640.1	641.0
					No Failure

FIGURE 33 - Steel Race Bearing Suspended After 641 Hours on Test

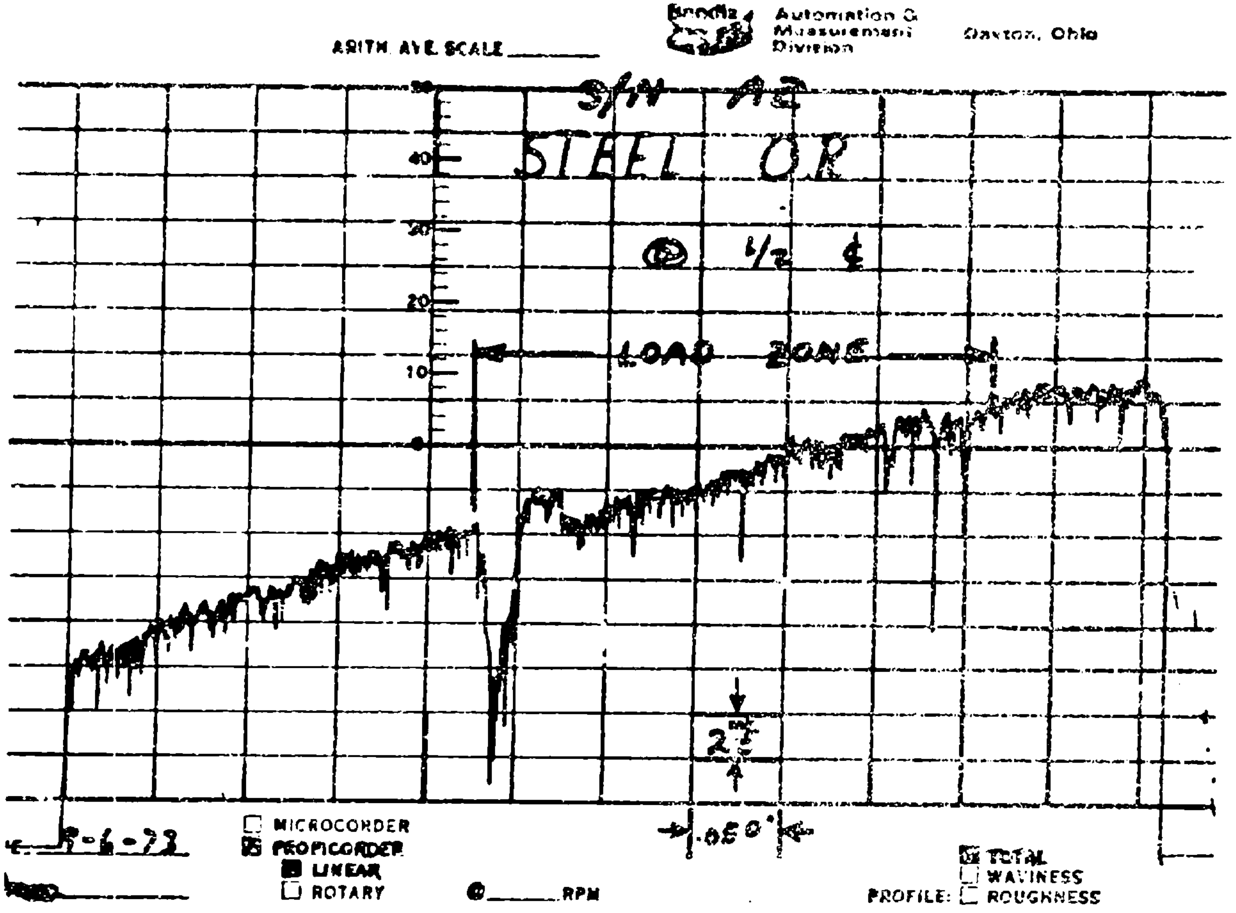


FIGURE 34 - Linear Proficorder Trace Across M-50 CVM Outer Steel Race A-2 After 641 Hours of Testing

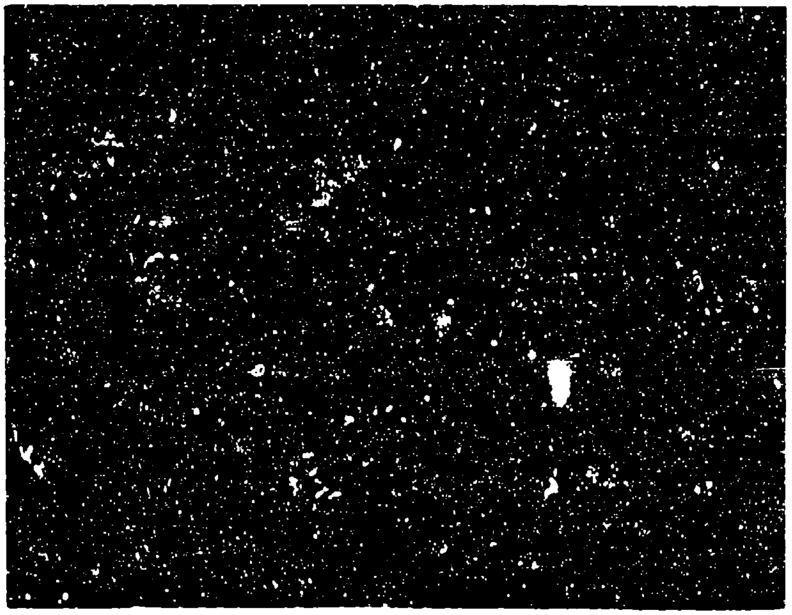


FIGURE 35 - Surface of Roller From A-2 Bearing After Test Suspension, SEM, 2000X.

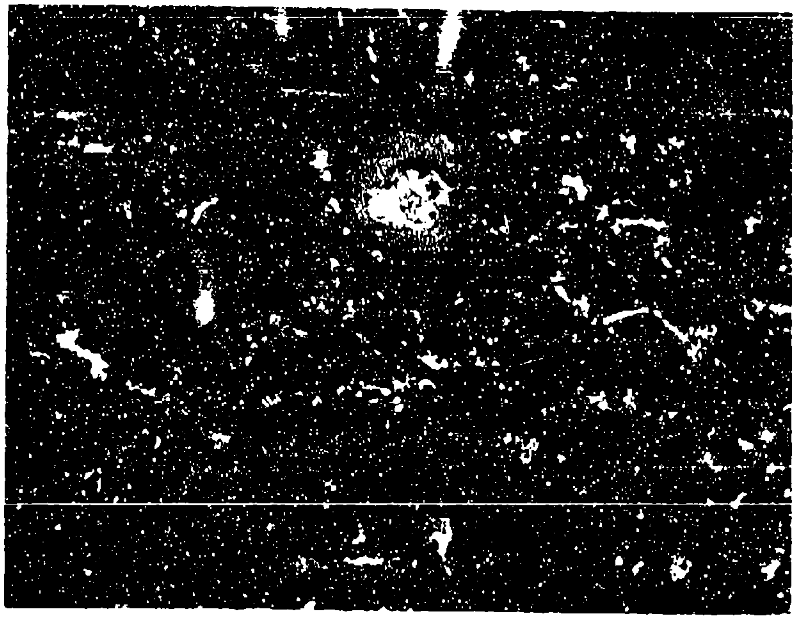


FIGURE 36 - Steel Race Wear Debris From A-2 Bearing, SEM, 1000X.

D. Test Results - Silicon Nitride Races and Rollers

Two of the three bearings having all silicon nitride rolling elements and races were tested under similar conditions as above without fatigue failure or unusual wear. The test set-up is shown in Figure 37. The third bearing, having the poorest track taper condition, was not tested. Both bearings were suspended from test after 62 hours and 331 hours. A detailed accounting of the test conditions is shown in Table XVII.

Bearing #2 was inadvertently dropped during removal from the test adapters. The result is shown in Figure 38. The ball support bearing had "fretted" to the shaft resulting in excessive force necessary to press it off. When it broke loose, the test shaft, remaining ball bearing and the test bearing inner race and rollers fell to the floor with an estimated minimum impact energy of 25 foot pounds. Although further testing of this bearing was impossible, if an all steel precision bearing had been dropped, it, also, would not have been tested further because of possible bearing damage.

Bearing #1 is shown in Figure 39 after 331 hours of operation. The outer race load zone can be seen and extended about 60 degrees of arc on both sides of the point of load application. Edge loading is not as visible as with the steel races. The wear in the load zone was measured at its maximum depth, under the point of load application, and found to be 25 millionths of an inch as shown in Figure 40. Inner race wear was not measured but visual inspection indicates that it is substantially less than for the outer race. A dye penetrant examination of the ceramic races and rollers after test suspension did not reveal any cracks. Bearing #1 is in excellent condition and could be tested further. Figure 41 shows the surface of a roller from Bearing #1 after test suspension. The relatively large smooth areas of Figure 24 have been worn away, revealing the microstructure and grain pull-out.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The achievement of long lives for hot-pressed silicon nitride in rolling contact fatigue studies confirms the assertion, made in last year's work, that finishing technique can control the fatigue life of silicon nitride. At a nominal Hertz stress of 700,000 psi, the fatigue life of NC-132 silicon nitride is eight times that of M-50 CVM steel. The primary mode of fatigue spall initiation in rolling contact studies with properly finished NC-132 silicon nitride is associated with Hertz crack formation. The low frequency of large inclusions in NC-132 silicon nitride decreases the incidence of inclusion initiated spalling. On the basis of the absence of fatigue spalling or Hertz cracking in

FIGURE 37 - Bearing Test Adapters and Silicon Nitride Race Bearing

TABLE XVII

Test Conditions: Silicon Nitride Races and Rollers

Bearing Number	rpm	Load lbs.	Temp. °F	Time Hrs.	Total Time Hours
1	10,000	500	178	20.0	20.0
	10,000	1000	179	2.0	22.0
	10,000	2500	174-178	309.5	331.5
					No Failure
2	1,200	500	175	0.7	0.7
	3,600	500	175	0.1	0.8
	5,400	500	175	0.1	0.9
	9,600	500	177	16.2	17.1
	10,000	1000	176	44.8	61.9

Shipped during routine inspection.

FIGURE 38 - Damaged Silicon Nitride Bearing, Chipped During Disassembly

FIGURE 39 - Silicon Nitride Race Bearing Suspended at 331 Hours

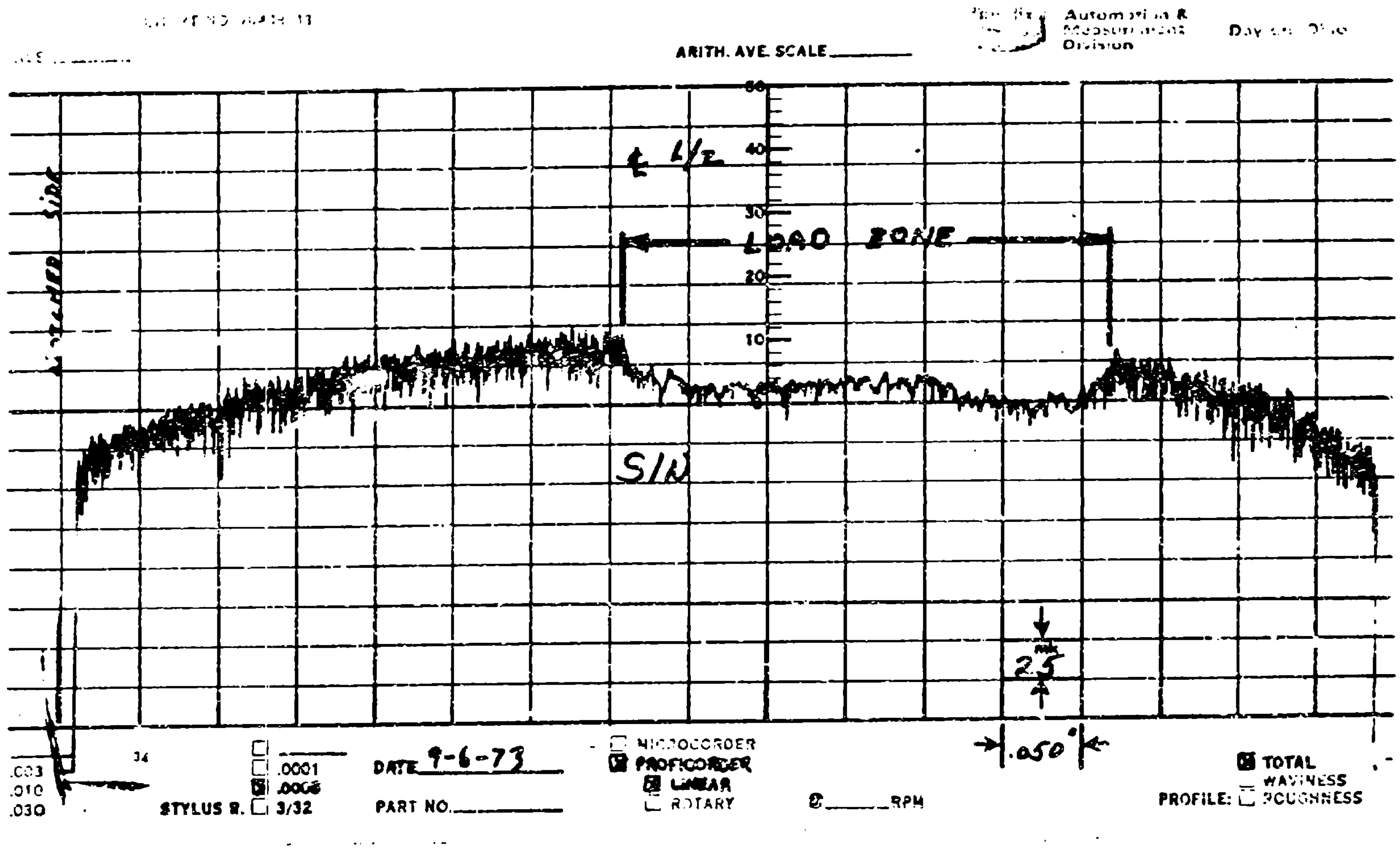


FIGURE 40 - Linear Proficorder Trace Across Silicon Nitride
Outer Race #1 After 371 Hours of Testing

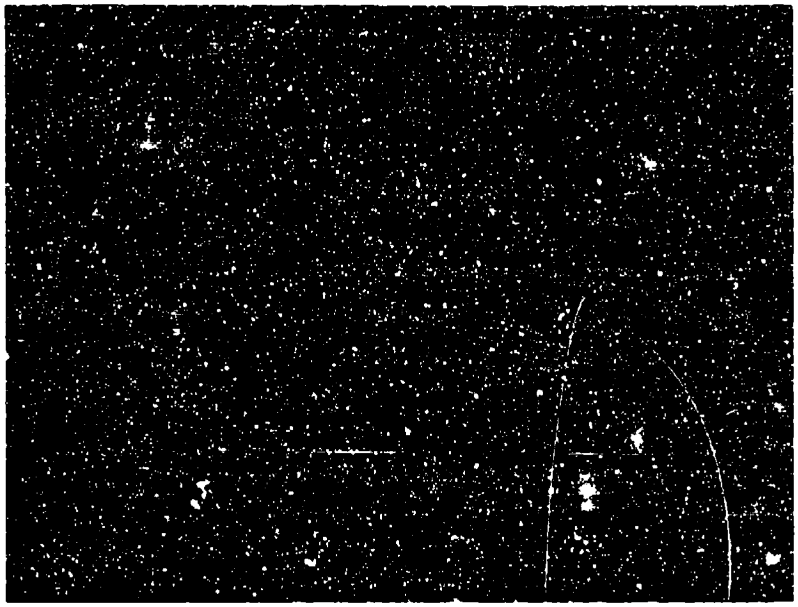


FIGURE 41 - Worn Surface of Roller From Bearing #1 After Test Suspension, SEM, 2000X.

NC-132 silicon nitride at a nominal 600,000 psi Hertz stress level for up to 93 million stress cycles, the silicon nitride may possess a threshold stress for fatigue failures. If a fatigue threshold does exist for silicon nitride, ceramic race or roller fatigue is not expected to be a problem in silicon nitride bearings. Wear is expected to be the major life controlling factor.

Full bearings, utilizing silicon nitride rollers, can be successfully designed and fabricated. Either steel race or silicon nitride race bearings with silicon nitride rollers are feasible.

The successful accelerated testing of full scale silicon nitride containing bearings has confirmed the promise of silicon nitride as a rolling contact bearing material. Although the silicon nitride containing bearings were limited in number and were not tested to failure, thereby preventing a rigorous statistical comparison with all steel bearings, the preliminary results indicate that the silicon nitride bearings compare very favorably to steel bearings.

B. Recommendations

The following recommendations for the additional development of silicon nitride containing roller bearings are made:

1) Establish the Weibull life distribution and failure modes for both types of silicon nitride containing bearings.

2) Study the wear of silicon nitride as a function of finishing techniques and lubrication under simulated bearing conditions.

3) Evaluate bearing performance after lubrication shut-off.

4) Examine the effect of compositional variations on the rolling contact bearing performance of silicon nitride.

5) Obtain field test data on the performance of silicon nitride containing roller bearings in engines or other mechanical devices.

APPENDIX I

Ceramics in Rolling Contact Bearings - Prior Work

Crystallized glass (Pyroceram) ceramic was examined by Zaretsky and Anderson[7] for possible use in high temperature applications. While the failure mode, a spall, was similar to that experienced with bearing steels and the scatter in life to failure was much less tha that experienced with bearing steels, the so-called L_{10} of the material was less than 10 percent of that of bearing steels. Appledoorn and Royle[8] confirmed these results in a later publication. These two studies as well as others with crystallized glass, including that by Carter and Zaretsky[9], indicate that if the L_{10} were at least equivalent to that of bearing steels, ceramics would be desirable because of the reduction in scatter of life to failure (associated with the absence of foreign inclusion) and because of the acceptable mode of failure. Crystallized glass perhaps was not a good candidate because of its low strength-modulus of rupture is less than 40,000 psi[10] - and low hardness - approximately 53 Rockwell C as reported in Ref. 7. In fact, if one can extract one of the more basic tenets of metal bearing practice, the crystallized glass would now not be considered because of its relatively low hardness.

Parker et al[11] conducted studies with three ceramics and one cermet for rolling contact applications with the objective being high temperature bearings. The ceramic materials were hot-pressed and cold-pressed alumina, both ninety-nine percent pure, and a two-phase sintered silicon carbide. This work was one of many that involved evaluation of aluminas, and KT silicon carbide, the latter manufactured by the Carborundum Company. Its results were representative of other work done and included five-ball tests at room temperature. Once again, life to failure for ceramics was found to have less scatter than that for bearing steels, but the L_{10} of the best material was only seven percent of that of bearing steels. The mode of failure was a spall but was attributed to a surface condition rather than subsurface stresses. Hot-pressed Alumina performed the best of the three, and this better performance was related to minimum porosity, and thus better surface finish and homogeneity.

In another study, Taylor et al[12] evaluated hot-pressed silicon carbide and hot-pressed alumina for service above 1000°F, well above the operating temperature of conventional liquid lubricants. Unfortunately, rolling contact evaluations were not conducted in a "standard" bearing environment.

Scott et al[13] conducted very preliminary four-ball tests with silicon nitride. While the results of these tests with the hot pressed form of silicon nitride were somewhat disappointing, the authors concluded further work with this material was in order.

More recently, Scott et al[14] performed additional four-ball tests on an unspecified grade of hot-pressed silicon nitride. Under unlubricated testing at a 550,000 psi Hertz stress at ambient temperature, the silicon nitride was the best of the materials evaluated, which included bearing steels. Wear was experienced at 280°C in an unlubricated condition but could be effectively suppressed with the use of MoS_2 lubricant. At very high loadings (1,000,000 psi nominal Hertz stress) with mineral oil lubrication, their material was reported to be an ineffective roller bearing material.

Parker and Zaretsky[15] presented preliminary results evaluating silicon nitride at 800,000 psi Hertz stress in a NASA five ball rig. The fatigue spall in the silicon nitride resembled those in typical bearing steels. The load capacity while approximately one-third that of typical bearings steels was significantly higher than previously tested ceramic materials for rolling element bearings. Additional studies are being pursued by these authors.

Wheildon et al[1] examined hot pressed forms of silicon nitride, silicon carbide and aluminum oxide as potential bearing materials. Silicon nitride showed excellent life in screening tests involving lubricated rolling contact fatigue, outperforming M-50 steel at comparable loads. Silicon carbide and aluminum oxide did not show as much promise as silicon nitride. The coefficient of Friction and wear rates for a steel-silicon nitride combination were comparable to those of a steel-steel combination. Proper surface preparation, which avoids severe sub-surface damage, and a high material density of silicon nitride were found to be essential for its outstanding rolling contact fatigue performance.

From the above mentioned studies, one can conclude that ceramics which provide better performance are those which have low to zero porosity, have a single homogeneous phase, and exhibit a hardness at least equivalent to heat treated bearing steel.

APPENDIX II

RCF Stress Calculations*

The maximum Hertz stress for the RCF contact geometry, under non-lubricated conditons, is given by:

$$\sigma = \frac{C_\sigma \ C_d \ P^{1/3}}{(L/M)^{2/3}}$$

where, σ = maximum Hertz stress in psi

P = load in pounds

$$L = \frac{1 - \gamma_1^2}{E_1} + \frac{1 - \gamma_2^2}{E_2}$$

where E_i and γ_i are the Young's modulus and Poisson's ratio, respectively, of the i-th body,

$$M = 1/D_1 + 1/D_1' + 1/D_2 + 1/D_2'$$

where D_i and D_i' are the two orthogonal diameters of curvature for the i-th body

C_σ and C_d = Geometric parameters determined from the diameters D_1, D_1', D_2, D_2'.

The parameters, C_σ and C_d, may be read from Figure A1.

Table A1 compiles the loading required to achieve the various maximum Hertz stress levels used in the RCF testing. The following values were used in the calculations:

$E_{steel} = 30 \times 10^6$ psi

$E_{silicon\ nitride} = 45 \times 10^6$ psi

$\gamma_{steel} = 0.29$

$\gamma_{silicon\ nitride} = 0.25$

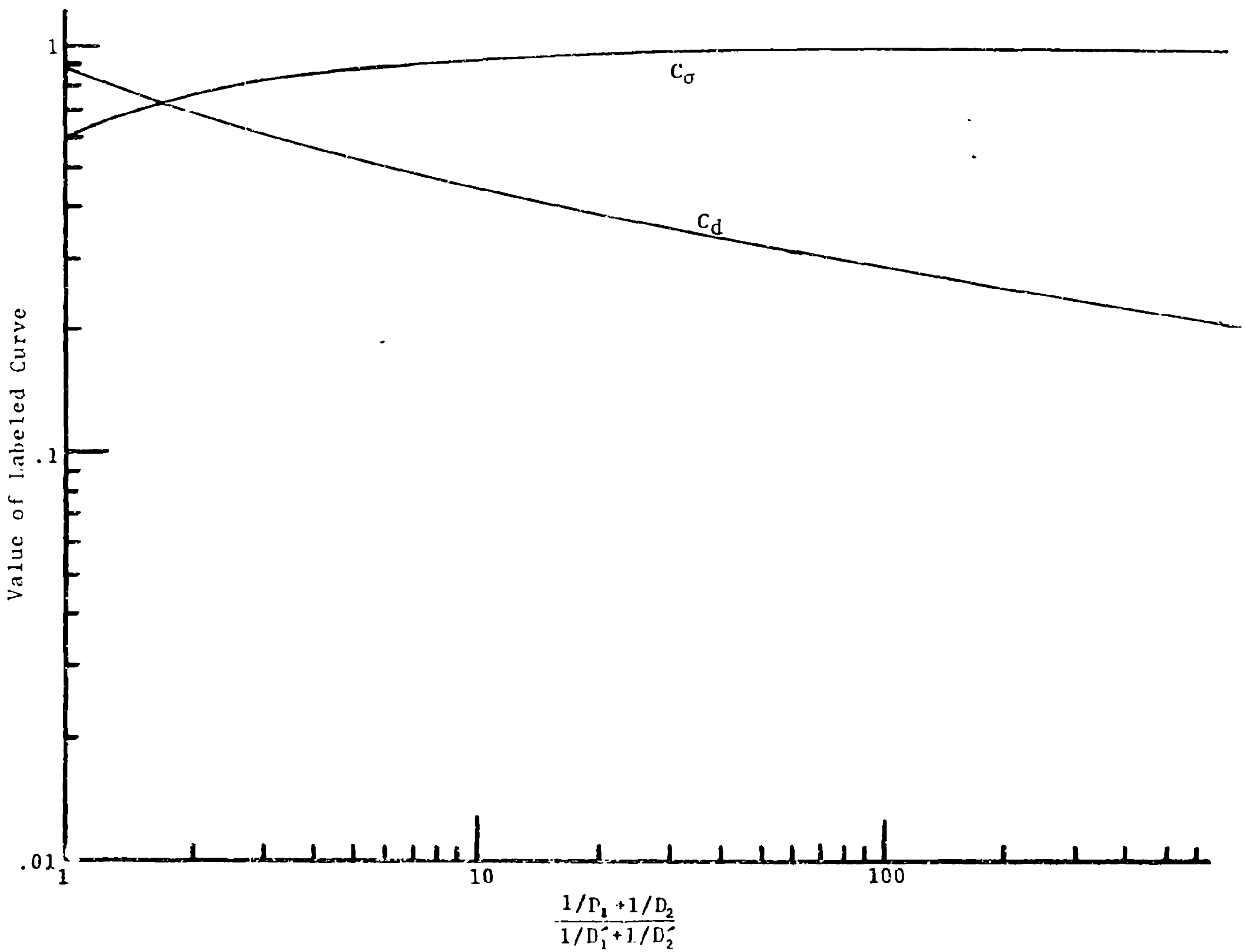
D_1 = 7" = diameter of loading wheel

D_1' = 0.5" = loading wheel crown diameter

D_2 = 0.375" = RCF rod diameter

$1/D_2'$ = 0.0 (infinite curvature along rod axis)

*Blackett, Charles, Unpublished Federal-Mogul Corporation Internal Report #8122, November 1962.



1
.1
.01
1
10
100
Value of Labeled Curve
C_σ
C_d
$\frac{1/D_1 + 1/D_2}{1/D_1' + 1/D_2'}$

TABLE AI

Bar Material	Wheel Material	Pounds Load to Produce Specified Hertz Stress			
		600M	700M	750M	800M
M-50	M-50	205	325	-	-
Si_3N_4	50	140	220	275	325
Si_3N_4	Si_3N_4	89	140	-	210

APPENDIX III

An AFBMA calculation for the L_{10} life of an all steel roller bearing may be obtained from the equation*:

$$L_{10} = \left(\frac{\text{capacity}}{\text{load}}\right)^n \times \frac{500 \text{ rpm}}{\text{bearing rpm}} \times 500 \text{ hours}$$

where, n = exponent for steel roller bearings = 10/3

capacity = 4020 pounds for steel

For the conditions of interest:

Load = 2500 pounds

Bearing rpm = 10,000 rpm,

an L_{10} of 120 hours may be found.

---

*Bower Roller Beari.., Catalog, 1963.

BIBLIOGRAPHY

1. Wheildon, W. M., Baumgartner, H. R., Sundberg, D. V and Torti, M. L., "Ceramic Materials in Rolling Contact Bearings", Final Technical Report under Naval Air Systems Command Contract N00019-72-C-0299, (1973).

2. Johnson, L. G., "Statistical Treatment of Fatigue Experiments", General Motros Report GMR-202, April, (1959).

3. Anti-Friction Bearing Manufacturers Association Catalog, Section 11, AFBMA, NY, NY.

4. Wilshaw, T. R., "The Hertzian Fracture Test", J. Physics D: Appl. Phys., 4, 1567, (1971).

5. Oh, H. L. and Finnie, I., Intl. J. Fracture Mech., 6, 287, (1970).

6. Frank, F. C. and Lawn, B. R., Proc. Roy. Soc. (London) 299A, 291, (1967).

7. Zaretsky, E. V., and Anderson, W. J., "Rolling - Contact Fatigue Studies with Four Tool Steels and Crystallized Glass Ceramic:, J. Basic Eng. 83, 603 (1961).

8. Appledoorn, J. K., and Royle, R. C., "Lubricant Fatigue Testing with Ceramic Balls", J. ASLE 2, 45 (1965).

9. Carter, T. L., and Zaretsky, E. V., "Rolling Contact Fatigue ife of a Crystallized Glass Ceramic" , NASA TN D-259 (1960).

10. Anon., "Pyroceram", Corning Glass Works, Corning, NY (undated).

11. Parker, R. J., Grisaffe, S. G. and Zaretsky, E. V., "Rolling--Contact Studies with Four Refractory Materials to 2000°F. ASLE Trans. 8, 208 (1965).

12. Taylor, K. M., Sibley, L. B. and Lawrence, J. C., "Development of a Ceramic Rolling Contact Bearing for High Temperature Use". ASME 61 Lubs-12 (1961).

13. Scott, D., Blackwell, J., and McCullagh, P. J., "Silicon Nitride as a Rolling Bearing Material - A Preliminary Assessment", Wear 17, 73 (1971).

14. Scott, D. and Blackwell, J., "Hot Pressed Silicon Nitride as a Rolling Bearing Material - A Preliminary Assessment", Wear, 24, 61, (1973).

15. Parker, R. J., and Zaretsky, E. V., "Rolling Element Fatigue Life of Silicon Nitride Balls - Preliminary Test Results", NASA TMZ-68174 (1972).